Studies To Increase The Flow Rate Of
Military Jet Fuel By Reducing

STUDIES TO INCREASE THE FLOW RATE OF MILITARY JET FUEL

BY REDUCING FRICTIONAL DRAG

by

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PREFACE

It is now well recognized that certain types of macromolecules, when added in relatively small concentrations to solutions flowing in turbulent motion, possess the property of reducing the friction drag of the fluid in which they are suspended or dissolved. As a result, the addition of these substances can significantly increase the capacity of a system to transmit fluids at normally turbulent flow rates.

The feasibility of utilizing this effect to reduce the time required to perform certain critical refueling operations encountered in military logistics support prompted this investigation. That the tactical vulnerability of a combatant force is at its peak during periods of logistic replenishment is well recognized by military logisticians. This is particularly true during periods involving underway refueling operations from a mobile replenishment group at sea, midair refueling of aircraft and the refueling of aircraft aboard aircraft-carriers at sea.

The original scope of this investigation envisioned an examination of the drag reducing effects of a number of viscoelastic polymers in several of the more common military fuels in use. It was further recognized that the effect these additives would have on the quality of the fuel would be of paramount interest. However, because of the time required to design, assemble and calibrate a flow system which would be suitable for investigation of the drag reduction phenomena, this scope was limited to the examination of a single high molecular weight polyisobutylene (Vistanex L-200) added to military jet fuel (JP-4). The effect of this additive on fuel quality was not investigated.

A variable pressure, single pass flow system was designed and constructed for use in this study. This type of system was selected in order to maintain similarity with tactical refueling operations. Further, the effects of mechanical degradation could best be observed in a single pass system since the fluid makes only one pass through the test section. Finally, flow behavior over a wide range of the turbulent flow regime could be observed yet fluid consumption and equipment cost

could be minimized. The apparatus was found to perform well in both the laminar and turbulent flow regimes when tested with liquids of well known fluid properties.

All drag reduction experiments were accomplished by observing the flow behavior of solutions containing 50 wppm of the high molecular weight Vistanex L-200 in military jet fuel. The results of the study indicate that a marked reduction in the viscous drag of jet fuel flowing in the turbulent regime can be achieved. It is anticipated that the time required to transmit fuel could be better than halved.

The polymer tested was found to be extremely sensitive to mechanical degradation. While the results of this study are not conclusive, a striking similarity between what has been termed "the diameter effect" and the effects of mechanical degradation was observed. A correlation suitable for dynamic scale-up to full sized flow systems was frustrated by this degradation/diameter effect. Further, it was found that mechanical devices producing extremely high localized shear rates could completely destroy the drag reducing effectiveness of the additive. Therefore, it was concluded that this type of a device should be avoided in any full scale flow system or, alternatively, injection of the additive should be accomplished downstream from such a device.

There were strong indications that a suppression of turbulent fluctuations might well be the main characteristic of drag reduction. Additional work with more precise equipment was recommended which would serve to verify this tentative conclusion.

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CHAPTER I

INTRODUCTION

The objective of this study was to investigate the effects on fluid flow caused by the addition of a minute quantity of a high molecular weight polymer to military jet fuel (JP4). The flow was observed in the turbulent flow regime corresponding to a range of Reynolds numbers from 10^4 to 10^5. In particular this thesis is concerned with the characteristics of frictional drag (or its reduction) as influenced by such an additive under conditions of flow in cylindrical tubes. The primary emphasis of this study has been to seek the factors which tend to influence the effectiveness of such additives in a common fuel in actual use, rather than to search for the mechanisms which might be responsible for the cause of drag reduction. Further, it was recognized that time would permit only a very limited examination of the influence of these additives since it would first be necessary to design, assemble and calibrate a flow system suitable for the investigation of the drag reduction phenomenon. However, it was hoped that this effort might become the basis for future work in this area since a calibrated system would be readily available.

LITERATURE SURVEY AND DISCUSSION

(a) Drag Reduction Defined The term "drag reduction" or "fluid friction reduction" has been used to describe a rather broad spectrum of rheological phenomena since first introduced in the technical literature in 1949. It is therefore necessary to consider two quite distinct classifications of fluids, purely viscous and viscoelastic, with which the term is frequently associated in order to clarify the definition as used in this thesis. The first classification consisting of fluids commonly described as "purely viscous" can be further subdivided into two categories. The fluids of the first category are said to obey Newton's Law of Viscosity and are broadly classified as "Newtonian Fluids." The behavior of such fluids can be described by the general power law or "Ostwald-de Waele" model (3):

$$\tau = -m\,(dv_x/dy)^n \qquad [1\text{-}1]$$

where $n = 1$ and m is a constant and $m = \mu$

This relationship states that the shear force per unit area (shear stress) varies directly with the negative of the velocity gradient. A more useful relationship, since it describes the shear stress/shear rate characteristics of laminar flow in cylindrical tubes in terms of measureable or derived quantities, is:

$$\tau_w = D\Delta P/4L = \mu\,(8V/D) \qquad [1\text{-}2]$$

or

$$R\Delta P/2L = \mu\,(4Q/\pi R^3) \qquad [1\text{-}3]$$

Results of extensive experimental tests of these fluids in turbulent flow through sand-roughed pipes were presented by Nikuradse in 1933. Friction factor data are conventionally presented as functions of Reynolds numbers in dimensionless plots using logarithmic scales with relative roughness as a secondary variable. Perhaps the most well known plots of this type are the "Moody Diagrams" (14) found in common engineering handbooks. (9)

Fluids in the second category, "purely viscous," are classified as "non-Newtonian" and can generally be described by the power law relation, equation [1-1], but without the restrictions that $n = 1$ and m be constant. Similarly, in terms of physical quantities more amenable to direct measurement:

$$\tau_w = D\Delta P/4L = m\,[2(3 + 1/n)\,V/D]^n \qquad [1\text{-}4]$$

After measuring ΔP as a function of V (or flow rate from which an average velocity can be derived) a plot of the variables $D\Delta P/4L$ versus $8V/D$ on log-log paper can be constructed which will reveal to which of these two viscous categories a fluid belongs. The popularity of the Ostwald-de Waele power law as a means of describing viscous fluid behavior now becomes readily apparent since it has been shown to correctly portray the relationship between shear stress and shear rate for many fluids over the broad range of shear rates commonly encountered.

Extensions of the experiments conducted by Nikuradse which include the behavior of non-Newtonian fluids have been the subject of more recent investigators. (4, 22) By using a "generalized" Reynolds number which has been shown to be a function of power law coefficients, m and n, Dodge and Metzner (5) have revealed the nature of the friction factor, "generalized" Reynolds number relationship for flow of non-Newtonian fluids through smooth cylindrical pipes. The results of the Dodge and Metzner studies indicate that:

(a) The generalized Reynolds number at which transition from laminar flow to turbulent flow is observed increases slowly from a value of 2100 for Newtonian fluids as the flow behavior index, n, decreases. (n is customarily defined as the index of non-Newtonian behavior.)

(b) At any given generalized Reynolds number in the turbulent flow regime there will be a decrease in the friction factor observed corresponding to a decrease in the flow behavior index, n.

These results might suggest behavior not totally unlike that associated with the drag reduction phenomenon.

Since the friction factors for purely viscous non-Newtonian fluids usually will be lower than those of Newtonian materials if $n<1$, it would appear as if the additions of solids or polymeric materials to a Newtonian solvent to yield a non-Newtonian fluid might serve to reduce pressure drop under turbulent conditions. In fact, however, the thickening action promoted by these additives generally will outweigh the friction factor reduction so that the actual pressure drop required to develop a certain flow rate will almost always be increased. As correctly commented upon by Savins (21) and Fabula and Hoyt (6), it is important to recognize the difference between non-Newtonian behavior and the drag reduction phenomenon, which is to be discussed shortly.

The high molecular weight, random-coiling polymers in solution appear to exhibit elastic characteristics in addition to the viscous characteristics which describe the behavior of most fluids. Hence, the second broad classification of fluids to be considered is termed "viscoelastic." It might be well to recall at this point that the properties of elasticity and viscosity are defined in terms of the response

of a fluid to an applied stress. The elastic response describes the tendency of a fluid to recover its former configuration upon removal of an applied stress. This recovery would be complete were it not for the viscous flow which begins when the stress is applied. The viscous flow is never reversed and may continue once the stress has been removed owing to the inertial properties associated with the fluid. Thus, an essential distinction between elasticity and viscosity is that the former describes a reversible process while the latter describes an irreversible property.

As might well be expected, very dilute solutions containing these viscoelastic polymers exhibit characteristics very closely identified with the fluid properties described as "Newtonian" by conventional viscometry i.e., $n = 1$, $m = \mu$ in Eq. [1-1]. Owing to the very low concentrations of polymer additives, the measured density and viscosity of a solution are very nearly the same as those of the pure solvent. At higher levels of concentration, they appear to impart non-Newtonian characteristics and while the assignment of "viscosity" as a fluid property to such fluids is somewhat nebulous, a thickening of the fluid is readily apparent. While investigating the characteristics of non-Newtonian fluids, both Dodge and Metzner (4, 5) and Shaver and Merrill (22) selected some additives which are now known to produce viscoelastic solutions. An apparent anomalous behavior was observed for the viscoelastic fluids when compared to the purely viscous fluids with approximately the same index of non-Newtonian behavior.

It is at this point that authorities appear to disagree on the meaning of "drag reduction." Shin (23) contends that if a polymer solution is "concentrated," it will display considerable gradient dependency of viscosity (the characteristic most commonly associated with non-Newtonian behavior) and that the assignment of viscosity for purposes of evaluating a Reynolds number is always equivocal. This suggests that the "flow anomaly" associated with the concentrated viscoelastic solutions observed by Shaver, Dodge, et al., might well stem from an imperfect model used to evaluate viscosity and generalized Reynolds number rather than an actual reduction in friction stress. In contrast, the Newtonian characteristics of the solvent are retained when dilute solu-

tions containing viscoelastic polymers are formed and the classical properties associated with viscosity and Reynolds number can be unequivocally evaluated in a conventional sense. Further, in very dilute polymeric solutions, the fluid properties generally used to describe fluid flow are very nearly equal to the properties of the pure solvent when subjected to conventional measurement techniques. Thus, the departure from conventional flow behavior associated with these extremely dilute solutions can very clearly be labeled "anomalous." This is not to suggest that these same characteristics do not occur in concentrated viscoelastic solutions. Indeed, the observations of Dodge (4) and Shaver and Merrill (22) and more recently those of Savins (21) and Rodriguez, Zakin and Patterson (20) strongly suggest that frictional stress reducing characteristics separate and apart from non-Newtonian behavior of purely viscous fluids are present in these concentrated solutions. However, from a practical standpoint, the final criterion of the effectiveness of such an additive must be measured by its friction reducing abilities as compared to the drag of the pure solvent in which it is dissolved. Thus, whether a final solution is considered Newtonian or non-Newtonian, dilute or concentrated, it is the frictional drag of that solution as compared to the frictional drag of the pure solvent which shall be used as the criterion to define drag reduction in this thesis.

(b) <u>Causes and Effects of Drag Reduction Phenomena</u> While there have been a number of attempts to isolate the precise mechanisms which give rise to the drag reduction phenomena noted in the literature, the exact mechanism is still not known. This, of course, is understandable considering that a microscopic phenomenon is being interpreted on the basis of macroscopic data fitted to a macroscopic or microscopic model.

The questions to be examined if one is to gain insight into the mechanisms which give rise to drag reduction, can now be stated more explicitly as: how the macroscopic fluid properties and flow behavior are related to the microscopic configuration and motion of the molecules; and, how the measurable macroscopic quantities such as fluid density,

viscosity and flow velocity can be shown to be consistent with a macroscopic or microscopic model of fluid flow.

The earliest published technical report available which attributes drag reduction to dilute polymer solutions appears to be that of B.A. Toms appearing in the Proceedings of the First International Rheological Congress. (25) Indeed, because of the pioneering research he conducted in this field, it is often referred to as the "Toms Effect." (7) In his paper, Toms presented data which indicated an observed increase in the rate of flow of monochlorbenzene at a constant pressure gradient caused by the addition of polymethylmethacrylate. The remarkable feature of these results was that this increased flow rate was a phenomenon observed only in the nonlaminar flow region.

Oldroyd (15) concurrently presented a paper suggesting that these unexpectedly high flow rates observed by Toms be explained in terms of anomalous behavior of a thin laminar layer at the tube wall when the mainstream of flow becomes turbulent. Oldroyd reasoned that, if the fluid is a solution containing a long chain linear polymer, an external constraint may be imposed by the wall of the flow system on the ways in which these long chain molecules can rotate. It might therefore be possible that an abnormally mobile pseudo-laminar sublayer, or boundary, of a thickness comparable with molecular dimensions could exist at the wall. This effect would then be macroscopically evident as an effective slippage at the wall. The flow rates as determined for conventional Newtonian fluids would have to be increased to account for this slippage.

Although the proposed velocity of slip might well explain the *macroscopic effect* of drag reduction, a departure from the accepted model of fluid flow is implied if this theory is used to describe the *microscopic cause*. In contrast to the model used to describe ordinary flow of a Newtonian fluid, it was visualized that the long chain polymers moved with translational motion, hence would slide or slip along the side of the wall. Subsequent investigation however, has failed to reveal any translational slippage. To the contrary, flow experiments conducted in both the laminar and turbulent flow regimes appear to confirm a flow model based on a zero velocity at the wall. Despite the fact that Oldroyd's slip mechanism as a cause for drag reduction has not

been given serious consideration for some time, there are relatively current texts which continue to refer to slip as being "important in some non-Newtonian flow problems." (3)

A second concept which might explain the mechanism or cause of drag reduction was first advanced by Davies, Ward, Atkinson and Blair (17) in reaction to Oldroyd's boundary layer theory. These gentlemen suggested the possibility that the Toms Effect is tied to the elasticity of polymer solutions, and although variations of this theory appear to be the most widely accepted today, the exact mechanism by which the elastic properties influence drag reduction is still not fully understood. In general, this theory holds that the elastic properties of the fluid absorb the kinetic energy of turbulent motion, thereby reducing the fluid transmission energy lost to turbulence. In other words, the irreversible friction losses due to turbulence are reduced because the energy associated with turbulent fluctuations has been reversibly stored in the fluid.

A third mechanism, the formation of a viscosity gradient, was apparently originally proposed by Shaver and Merrill (22) though it is discussed in some detail by Shin (25) under the heading "Anisotropic Viscosity." This theory stems from Merrill's suggestion that the local viscosity normal to the direction of shear might well be substantially increased through elongation of the randomly coiled macromolecules even though the viscosity parallel to the direction of shear is very nearly identical to that of the solvent. Thus, the high perpendicular viscosity can reduce turbulent fluctuations in that direction. Since the turbulent fluctuations are randomly directed, the orientation of the elongated molecules will also be random.

During the early 1960's, the Navy became particularly interested in the drag reduction phenomenon because of its possible influence on ship and torpedo performance. Fabula and Hoyt (6) of the Navy's Ordnance Test Station at China Lake, California, were particularly instrumental in surveying many water soluble drag reducing additives. As a result of their experiments conducted with aqueous polymer solutions, general rules were developed as to the type of material likely to be effective. In general, it was concluded that at least three

significant parameters affect the ability of a polymer to lower the turbulent frictional resistance of the fluid in which it is dissolved: linearity, molecular weight, and solubility. The "long chain" materials have an essentially unbranched molecular structure of high molecular weight when added to solvents in which they can be fully dissolved, appear to produce the most marked drag reduction effect. A review of the work of Fabula and Hoyt also reveals that: (a) drag reduction effectiveness tends to improve with increased concentrations up to a certain concentration level, after which any further increase in concentration level will result in decreased effectiveness; (b) at concentration levels less than the "optimum" concentration for any given additive, the friction factor versus Reynolds number curves are roughly parallel to, but *lower* than, the friction factor curve for the pure solvent flowing in the turbulent flow regime; (c) at concentration levels above the optimum concentration the friction factor curves are roughly parallel to, but *higher* than, the extended laminar fluid flow curve of the pure Newtonian solvent. Additional effects which appear to be more related to the flow system than to the fluid are also commonly observed:

(b) For a given solution which exhibits drag reduction characteristics the drag reduction effect is more pronounced as the diameter of the flow system is increased.

(b) For a given solution and flow system, the drag reduction effect becomes more pronounced as flow rates are increased. However, there appears to be a maximum tolerable shear rate associated with each flow system beyond which the drag reducing effectiveness appears to decline.

The more recent work of Shin (25) has served to quantify some of these qualitative observations, particularly with respect to defining the significant characteristics of a "dilute," "concentrated," "critical" and "optimum" solution. Shin's results suggest that the key to the question of whether the polymer solution is dilute or concentrated depends on the critical concentration which corresponds to the condition that each polymer molecule (having been assigned an effective spherical

diameter which is of the order of magnitude of its r.m.s. end-to-end distance) is brought to a spherical packing of 74%. In other words, the random coils touch each other, but are otherwise unchanged. When the polymer concentration is less than the critical concentration, it is considered "dilute." It is when a solution is "concentrated" that it will display considerable gradient dependency of viscosity or non-Newtonian behavior. On the other hand, polymer solutions less than one third of the critical concentration appear to display either negligible or undetectable gradient dependency of viscosity. While there was no direct correlation achieved between the optimum concentration and critical concentration, the optimum concentration was observed to be generally one tenth to one hundredth of the critical concentration. For example, the critical concentration of polyisobutylene L-200 in cyclohexane was found to be 520 wppm; the optimum drag reduction effectiveness over the limited shear rates investigated was found to be 35 wppm. As was emphasized by Shin, it is not commonly recognized that the critical concentration of solutions of polymers having molecular weights in the millions is small. Indeed, 0.1% polymer solutions are usually "concentrated" as defined by Shin.

In even more recent work, Rodriguez et al. (20) appear to have achieved a very useful correlation between drag reducing characteristics for turbulent flow in a pipe and measurable properties of the polymer solution and flow system. They have successfully correlated friction reduction behavior of a viscoelastic solution with a modified "Deborah number" defined as:

$$N_{Db} = V\,\tau_1/D^{0.2} \qquad [1\text{-}5]$$

Fabula et al. (7) and more recently Hershey (8), Astarita (2) and others have suggested that fluid friction reduction occurs when the relaxation time of the polymer molecules in solution exceeds a characteristic flow time of the experiment. The relaxation time of the polymer solution represents the relative amounts of viscous and elastic response. Characteristic flow time has been taken as the reciprocal of the shear rate at the wall. The problem has been that of identifying specific physical quantities susceptible to direct measurement, which would be

characteristic of fluid relaxation time. Park (13) has shown that intrinsic viscosity will not yield a favorable correlation when evaluating concentrated polymeric solutions. Yet the basis for determining a measure of relaxation time (τ_1) in the Rodriguez correlation would appear to be intrinsic viscosity (though fluid velocity and flow system diameter are, of course, reflected in the modified Deborah number). There would appear to be some disparity between the results of Park and Rodriguez. It would be interesting to investigate the drag reducing capabilities of Carbopol using the Rodriguez correlation since this additive would appear to be ideally suited to promote drag reduction, though none has been observed in Carbopol solutions to date!

SCOPE AND LIMITATIONS OF EXPERIMENTAL WORK

The original scope of this investigation envisioned an examination of the drag reducing effects of a number of polymers in several of the more commonly used military fuels. It was further recognized that the effect of these additives would have on the quality of the fuel would be of paramount interest. However, it would first be necessary to design, assemble and calibrate a flow system which would be suitable for investigation of the drag reduction phenomena. Because of the time involved in this phase of the work, the original scope was limited to a brief examination of a high molecular weight additive in military jet fuel at a concentration of 50 weight parts per million.

Time also placed important limitations on the type of flow system which could be assembled and used for drag reduction experiments. Although a closed loop, recirculating type of flow system, patterned after those of Dodge (4) or Melton and Malone (12) was initially considered, it became clear that the time required to obtain and assemble the equipment needed for such an elaborate system would be excessive. It might also be pertinent to note that systems which provide for a recirculation of the polymeric solution will not permit as detailed an examination of such important factors as mechanical degradation as is permitted in a single pass flow system. This is particularly true if recirculation is accomplished by a mechanical device generating high localized shear rates. For these reasons, it appeared that a single

pass system patterned after a variable pressure capillary tube viscometer (such as the one used by Dodge for viscometric measurements) would be the most practical system which could be assembled in a reasonable time period. Hypodermic tubes for use as test sections were readily available as was a supply of bottled nitrogen gas for use as the driving mechanism. Since it was desirable to design a flow system capable of providing a means of observing the flow behavior in the well developed turbulent regime, a computerized model of a capillary tube viscometer was developed through which the design parameters affecting fluid flow over a range of Reynolds numbers up to 10^5 could be examined. The maximum driving pressure, of course, could not exceed the pressure provided by the bottled nitrogen. Further, the largest fluid reservoir available capable of withstanding the pressure from the bottled nitrogen appeared to be an empty nitrogen cylinder which had an estimated capacity of between 10 and 15 gallons.

CHAPTER II

DESIGN, CONSTRUCTION, CALIBRATION, AND OPERATION OF FLOW SYSTEM

PRELIMINARY DESIGN CONSIDERATIONS

Previous experimental work involving observations on drag reduction have generally been performed on three distinctly different types of flow systems:

(a) The immersed rotating disk or cylinder.

(b) The closed loop, recirculating flow system.

(c) The open loop, single pass flow system through small capillary tubes.

Generally, these involved a type of rotational shearing boundary or cylindrical tube flow system, each of which has its own distinct advantages and disadvantages. *This* study was undertaken with a specific application in mind--the feasibility of reducing the time required to perform certain critical refueling operations encountered in the logistics support of tactical military maneuvers. A characteristic of these operations is the "one shot" transmission of fluid through relatively short fuel lines. A modification of the latter system was selected for the experimental work in this study in order to achieve a degree of similarity to the characteristics of tactical military logistical systems.

The system consisted of a set of stainless steel hypodermic tubes which could be connected to a high pressure reservoir into which the fluid to be examined was loaded. The fluid was forced out of the reservoir by a siphoning technique which was achieved by connecting the reservoir to a source of bottled nitrogen (see Figure 2-1).

An energy balance on a capillary tube flow system reduces to the following form, considering steady state, isothermal flow and neglecting the effects of hydrostatic pressure:

$$(P_2-P_1)/\rho + (K/2g_c)(V_2^2 - V_1^2) + 2fV_2^2L/g_cD = 0 \qquad [2\text{-}1]$$

where points 1 and 2 refer to the entrance and exit to the flow tube.

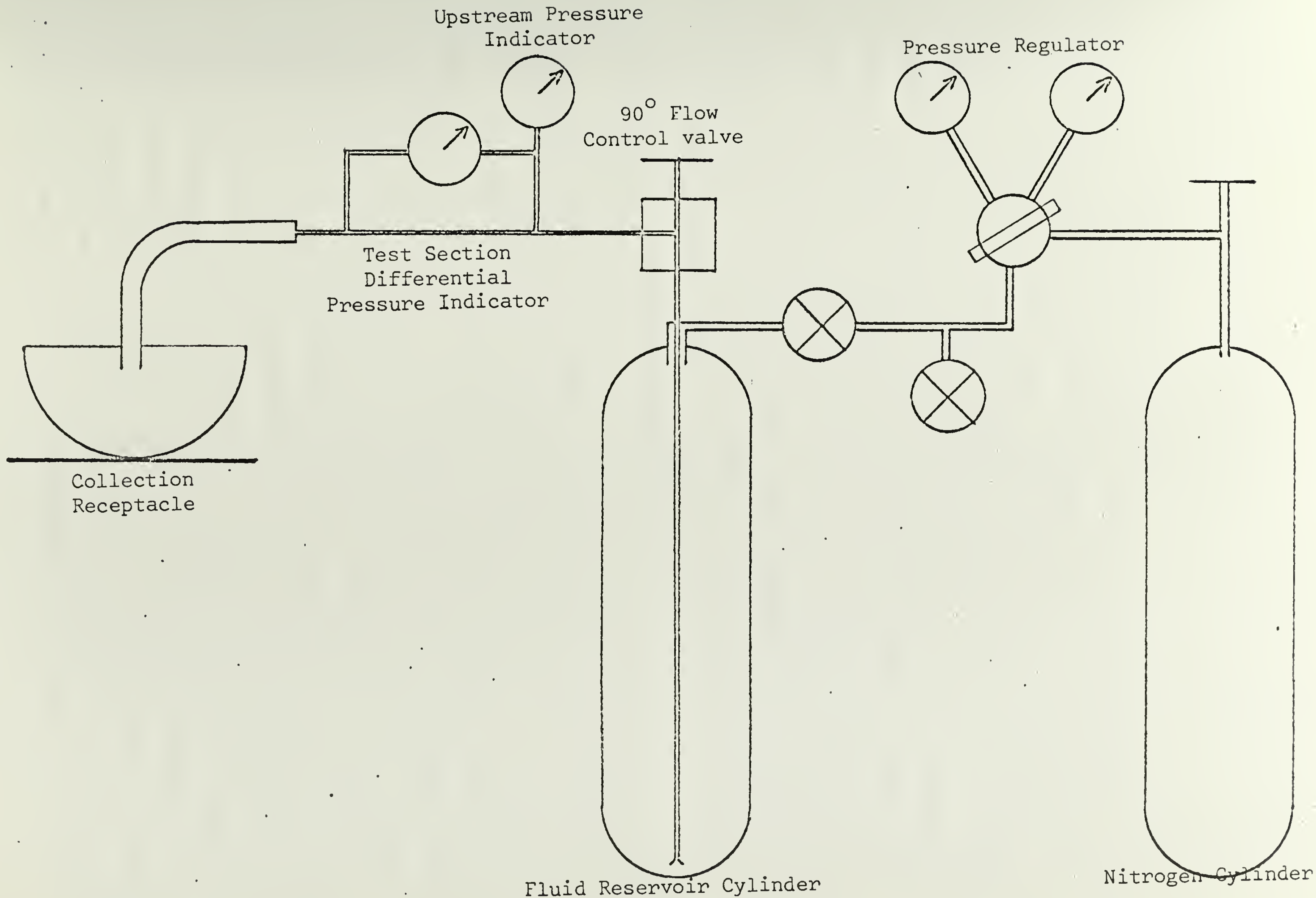

Figure 2-1 Schematic of Variable Pressure Flow System

In capillary tube measurements, it is customary to measure the total pressure applied to the reservoir chamber (P_1) and to consider the velocity in the reservoir (V_1) essentially as zero. Equation [2-1] then reduces to:

$$\Delta P = (\rho V^2/2g_c)\ (K + 4fL/D) \qquad [2\text{-}2]$$

The applied pressure then is used to overcome viscous resistance to flow within the tube and to provide the kinetic energy of the stream as well as the entrance and exit losses. These latter forms of energy are usually accounted for in the variable K. For ordinary laminar Newtonian flow probably the most widely accepted value of K is 2.24 (4). Unfortunately, the appropriate value of the total correction to account for kinetic energy and entrance and exit effects is somewhat in doubt for non-Newtonian and viscoelastic fluids (24). One can of course, place a lower limit on the value, that of 1.0 for a kinetic energy correction corresponding to a perfectly flat velocity profile (thus, a correction of $\rho V^2/2g_c$) Dodge (4) arbitrarily assigned a correction corresponding for the combined entrance, exit and kinetic energy effects of 1.5 $\rho V^2/g_c$ corresponding to a value of K equal to 3.

The ideal solution to this dilemma is to make the unknown value of K insignificant when compared to the 4fL/D term. In the laminar regime--for example at a Reynolds number of 800--f takes on a vlaue of 0.02. A length to diameter ratio of 1:1000 will result in a value of 4fL/D =80. Under these conditions, the widest conceivable error for K is probably less that 1%. If kinetic energy, exit and entrance effects are completely disregarded, the error would be less than 3%. On the other hand, in the turbulent regime with a drag reduction mechanism operative, the observed Fanning friction factors will frequently be less than 0.002. The same uncertainty in K as in the previous example will now result in an error of almost 8%. Further, it was found that an L/D ratio in excess of 200 could not be tolerated if the goal of observations extending to a Reynolds number of 10^5 was to be achieved for the full class of fuels originally envisioned. The uncertainty in K introduced by this new criterion could perpetuate an error of as much as 20%. Specially designed flow tubes with pressure ports located well downstream

from the entrance to the tube obviated the need to consider these corrections.

It might be pertinent to note that drag reduction experiments performed in a capillary tube rheometer at the University of Minnesota were reported in 1964 (19). The flow tubes were 1000 diameters in length in all cases. The report indicates that this "arbitrary selection of length was based on the recognition that fluid characterization errors contributed by entrance, exit, etc., diminished with increasing length while errors contributed by shear degradation might increase with length." However, the highest Reynolds number achieved in this apparatus with drag reduction effects operative was approximately 25,000.

A computerized model of a capillary tube flow system was developed through which preliminary design concepts could be tested for feasibility and practicality.

The computer model used for preliminary design was expanded as the final design of the actual flow system progressed, so that the effect of each design feature could be tested in advance of final construction. Therefore, computer program number 1 in Appendix A accounts for the design characteristics peculiar to the permanently installed portions of the flow system. This program can be used for two different purposes:

(a) To provide the reservoir pressure which will be required to operate the flow system at a given Reynolds number.

(b) To test the effect that variations of flow tube characteristics such as flow tube diameter, entrance length, exit length, and test section length will have on the performance of the flow system.

The former feature is designed to assist the operator of the flow system by providing the minimum weight or volume of fluid required to meet the criterion that the flow time for the run last at least 100 seconds, and by providing the pressure regulator setting required to achieve the flow regime (at a given Reynolds number) desired. The latter feature is provided to serve as a guide to the design and expected performance of new flow tubes to be used with this flow system. In either case, if the system limitations of available pressure or reservoir capacity are exceeded, the program will automatically signal such a condition

to the operator. A sample write out from this program is included in Table 2-1.

DISCUSSION OF SUPPORT EQUIPMENT USED AND CALIBRATION TECHNIQUES EMPLOYED

Fluid flow rates were determined by timing the flow of a predetermined quantity of fluid with a Galco stop watch (Chemical Engineering Department #110). The watch dial indicated time in increments of 0.2 seconds but there was a sufficient spread between marked increments to allow interpolation to the nearest 0.1 second. A predetermined criterion was imposed: that a run must take at least 100 seconds to insure that the precision of the time measurement was 1 part in 1000. The decision as to whether a volumetric or weight measurement would be taken using 100 and 500 ml graduated cylinders, a 2000 ml volumetric flask and a 4000 Erlenmeyer flask which was calibrated with the 2000 ml flask and marked at the 4000 ml level. When it was determined that the rate of flow would be too great to permit a time measurement of 4000 ml in at least 100 seconds, a weight measurement of fluid flow was taken using a Fairbanks Morse and Company 200 pound capacity scale, serial number G 403886, code 528. This scale contained marked increments of 1/16 pound with a sufficient spread between the marked increments to permit interpolation to the nearest 1/32 pound. A fluid sample of at least ten pounds was used as a basis for determining the rate of flow when measurements were taken, using a ten gallon stainless steel container to collect the sample of fluid. Comparison of the volumetric and weight measurements used to determine flow rate, established by weighing a 4000 ml fluid sample of carefully measured density, indicated the percent difference to be 0.6%. This difference corresponded to the minimum weight discrimination believed achievable on the Fairbanks Morse Scale (1/32 pound).

Fluid densities were measured with a Westphal balance obtained from the W. M. Welch Scientific Company. The weights were identified by serial number 4028A and the bulb was numbered 472 WHR. This balance was

TABLE 2-1

MODEL OF EXPECTED FLOW PERFORMANCE

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406
ENTRANCE LENGTH 3.997
EXIT LENGTH 1.332

FLUID PROPERTIES--VISCOSITY (CP) 1.000
DENSITY (GM/CC) 1.000

REYNOLDS NUMBER	AVERAGE VELOCITY (FT/SEC)	FLOW RATE (GAL/MIN)	EXPECTED DIFFERENTIAL PRESSURE (PSI AND/ IN. OF HG.)		AMOUNT OF FLUID REQUIRED (POUNDS AND/ LITERS)		REQUIRED RESERVOIR PRESSURE (PSI)
200.0	0.5	0.0	0.05	0.11	0.0	0.021	0.1
400.0	1.0	0.0	0.10	0.23	0.1	0.043	0.2
600.0	1.5	0.0	0.15	0.34	0.1	0.064	0.3
800.0	1.9	0.0	0.21	0.45	0.2	0.085	0.5
1000.0	2.4	0.0	0.26	0.57	0.2	0.106	0.6
1200.0	2.9	0.0	0.31	0.68	0.3	0.128	0.7
1400.0	3.4	0.0	0.36	0.79	0.3	0.149	0.9
1600.0	3.9	0.0	0.41	0.91	0.4	0.170	1.0
1800.0	4.4	0.0	0.46	1.02	0.4	0.191	1.1
2000.0	4.8	0.0	0.51	1.13	0.5	0.213	1.3
20000.0	48.5	0.3	42.71	94.30	4.7	2.127	111.2
40000.0	96.9	0.7	143.65	317.20	9.4	4.253	390.5
60000.0	145.4	1.0	292.05	644.90	14.1	6.380	816.2
80000.0	193.9	1.3	483.17	1066.93	18.8	8.506	1379.0

AT AND ABOVE A REYNOLDS NUMBER OF 80000.0 THE REQUIRED RESERVOIR PRESSURE EXCEEDS THE AVAILABLE SUPPLY

initially calibrated by using distilled water, the density of which has been established accurately (16). The balance was placed on a smooth aluminum plate in a semi-enclosed cabinet to minimize environmental disturbance. The calibration was checked periodically during the research and calibration phases to insure against calibration shift caused by accidental movement. Using this balance, densities were measured in increments of 0.0001 grams per cubic centimeter up to a maximum of 1.8999 grams per cubic centimeter.

Temperatures of both the environment and the fluids were taken using a Princo 15-30°C thermometer calibrated in increments of 0.1°C with a sufficient spread between marked intervals to permit interpolation to the nearest 0.05°C.

Three different pressure regulators connecting the nitrogen source cylinder with the fluid reservoir were used depending upon the range of pressures required to drive the fluid through the tubes. Regulated pressures of 200-1500 pounds per square inch were attained using a Hoke-Phoenix 0-3000 psi regulator, style 521 serial number N296C. Pressures of 75-175 psi were obtained through the use of a REGO 0-400 psi regulator, type XL. A Victor Equipment Company 0-60 psi regulator was used when pressures ranging from 10-60 psi were required.

Viscosity measurements were taken with a calibrated Cannon-Fenske capillary tube viscometer number 25/J680. The supplied calibration constant of the viscometer was 0.002225 centistokes per second at 100°F, and 0.002218 centistokes at 210°F. The calibration constant at 70°F obtained through linear extrapolation of supplied values was determined to be 0.002227 centistokes per second.

A series of calibration runs to check this value was conducted using distilled water for which accurately measured data on viscosity and density as a function of temperature was readily available (16). A computer program (program number 2 in Appendix A) was then prepared which would accept values of measured time and temperature and the corresponding known values of viscosity and density of the distilled water. From this information an average calibration constant was determined for the viscometer over the environmental temperature ranges encountered. The results of these calibration runs are included in Table 2-2. The

TABLE 2-2

RESULTS ON THE CALIBRATION OF NO. 25/J680
CAPILLARY TUBE VISCOMETER

FLOW TIME (SECS)	FLUID TEMP. (DEG.C)	STANDARD DENSITY (GM/CC)	STANDARD VISCOSITY (CP)	KINEMATIC VISCOSITY (CS)	COMPUTED CALIBRATION CONSTANT (CS/SEC)
431.4	21.6	0.9979	0.9669	0.9690	0.0022461
431.6	21.6	0.9979	0.9669	0.9690	0.0022451
432.8	21.8	0.9978	0.9623	0.9644	0.0022283
431.0	22.3	0.9977	0.9510	0.9532	0.0022116
426.0	22.6	0.9977	0.9444	0.9466	0.0022220
424.0	22.9	0.9976	0.9378	0.9400	0.0022170

COMPUTED ARITHMETIC AVE. CALIBRATION CONSTANT 0.0022283

average calibration constant of 0.002228 was used throughout the experimental phase of this study as the basis for determining viscosity with the Cannon-Fenske viscometer.

The pressure and differential pressure measuring instruments used in these experiments include a Heise 0-2000 psi bourdon pressure gage number H2939R, a Midwest Instrument 0-1000 psi differential bourdon pressure gage and a 50 inch glass manometer tube suitable for safe use at pressures corresponding to approximately two atmospheres. Both bourdon gages are marked to indicate increments of 5 psi over their entire range. The spread of the marked increments on the Heise gage is sufficient to permit reliable interpolation to within 1 psi while the design of the Midwest gage is such that a reliable interpolation to within 2 psi was the best accuracy believed attainable.

The Heise and Midwest gages were initially calibrated against a precision dead weight pressure measuring instrument, Ruska Balance #11516 with piston #B3-212, in the range from 100-1000 psi. While the Heise gage proved to be in exact agreement (within the 1 psi limit attainable for this gage) over the entire range considered, the corresponding readings taken with the Midwest gage raised a serious question of repeatable reliability. In order to establish a statistical base from which to judge the repeatability and usefulness of this gage, a series of recalibration runs were conducted. The Heise gage and Midwest gage were connected in parallel to a source of bottled nitrogen through the Hoke-Phoenix pressure regulator and the pressure was systematically raised and lowered over a range from 0-700 psi. The Heise gage was used as a secondary standard against which the performance of the Midwest gage could be measured. The results of this calibration are indicated in Figure 2-2. A mechanical hysteresis of 2 psi over this pressure range is readily apparent.

While the statistical scatter was considerable in the lower pressure ranges, it was decided that the repeatability was sufficiently good above the 75 psi range to justify the continued use of this gage. However an allowance providing for the observed statistical uncertainty has been included in all calculations derived from values measured with this gage. While it is recognized to be the measuring instrument with the

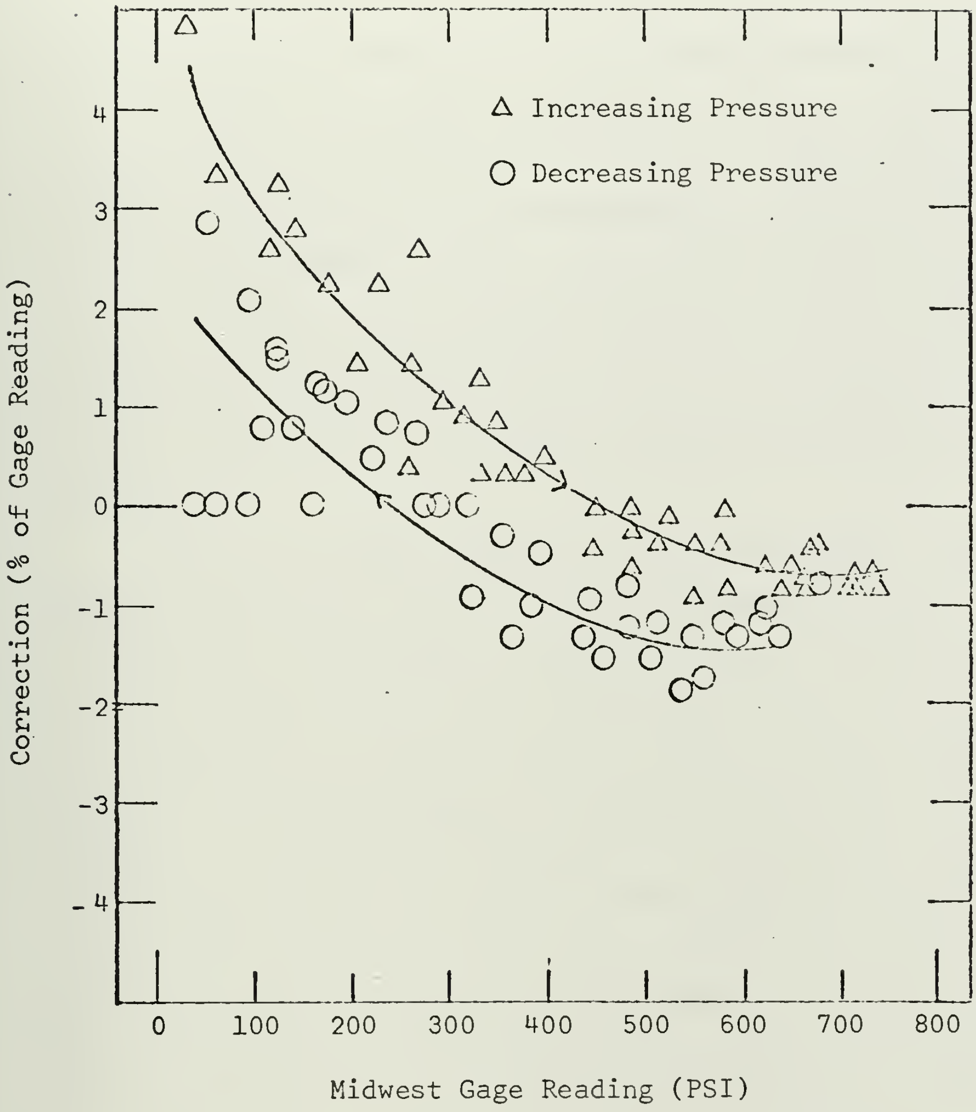

Fig. 2-2. Calibration Curves For Midwest Differential Pressure Gage

least desirable characteristics of all the equipment used, it was the only differential pressure gage available that was capable of measuring the high differential pressures expected to be encountered in the course of the experimental investigation. Further, time limitations would not permit the further delays which would be required to obtain, install and calibrate a different gage.

CONSTRUCTION AND CALIBRATION OF THE VARIABLE PRESSURE FLOW SYSTEM

A specially adapted high pressure nitrogen cylinder was employed as the fluid reservoir of the flow system. A safe working pressure of 2200 pounds per square inch was determined by tests conducted in July of 1962. The capacity of the cylinder was determined to be 1.78 cubic feet (111.5 pounds of tap water measured at 17.9°C). The exit to the nitrogen cylinder was fitted with a specially designed cap capable of receiving nitrogen gas under high pressure and discharging the sample fluid to a flow tube. A detailed drawing of the cap is shown in Figure 2-3.

One of the unique features of the flow system is the use of specially constructed tubes (detailed drawings of these tubes are shown in Figure 2-4). Hypodermic tubing with inside diameters varying from 0.054 up to 0.106 inches was obtained from the C. A. Roberts Company. Five tubes were constructed each with test sections of approximately 100 diameters, entrance lengths of 75 diameters and exit lengths of 25 diameters. A small hole was drilled at either end of each test section to which 1/8 inch O. D. stainless steel tubing was connected through 5/16 inch O. D. copper sleeves. The sleeves were reamed to snugly enclose the tubes, thereby providing support to the flow tubes as well as to the 1/8 inch tubing through which pressure measurements could be taken. The exit end of the flow tube discharged to a larger tube which was used to carry and deflect the efflux to a collection receptacle. The entrance end of the tube was fitted into a 3/8 inch Autoclave Engineering plug fitting which could then be assembled into an Autoclave series 30, 90° angle valve. The entrance rim of the Autoclave plug was rounded to meet the tubes thereby minimizing the disturbance

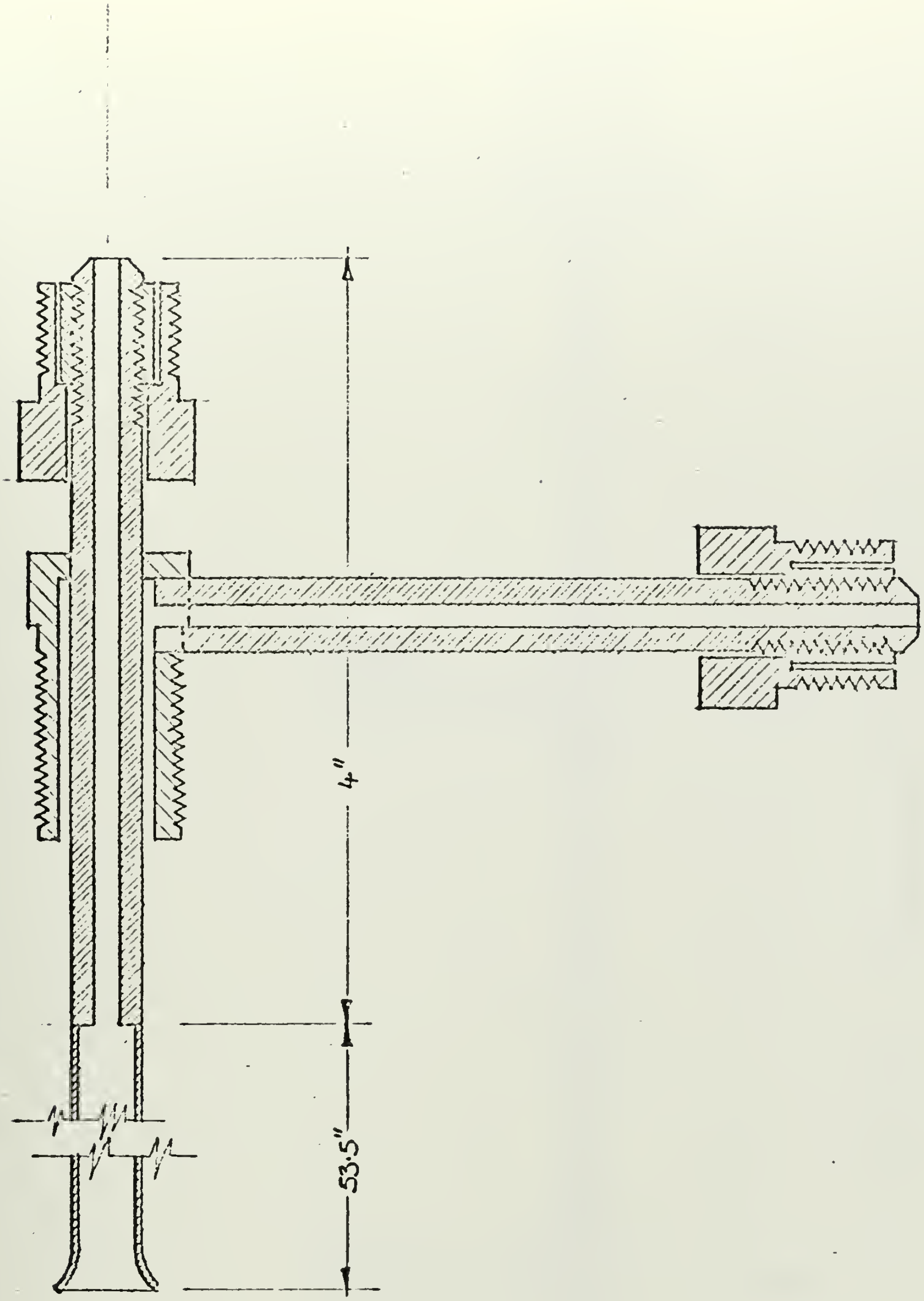

Figure 2-3   Engineering Drawing of Siphon Cap

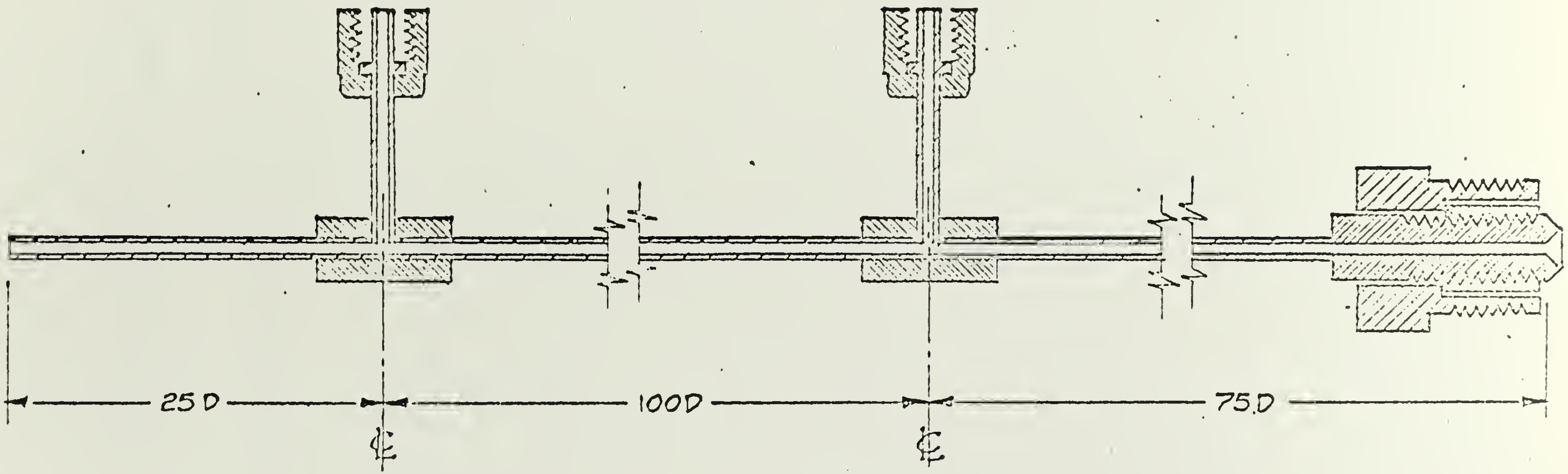

Figure 2-4   Engineering Drawing of Flow Tube

caused by an abrupt decrease in flow diameter at that particular point in the flow system. Hypodermic tubes with an outside diameter very nearly equal to the inside diameter of the flow tubes were used to deburr and polish the flow tubes after they had been constructed and during their experimental use.

The length of the test section of the flow tube was measured to better than 1/64 inch using a precision machinist's ruler. However, since the internal diameter of the hydraulic tubing supplied by the manufacturer was guaranteed to be accurate within limits of approximately ±0.002 inches, it was necessary to determine this measurement more precisely by conducting flow runs in the laminar flow regime. For this purpose tap water was loaded into the fluid reservoir and forced through the flow tubes at Reynolds numbers no greater than 2,000. A manometer containing colored carbon tetrachloride which had a measured density of 1.557 grams per cubic centimeters was connected across the pressure ports of the flow tube. Since the difference in density of the manometric fluid and the tap water was approximately 0.56 grams per cubic centimeters, this device provided a very sensitive and accurate means of determining the pressure differential across the test section.

A computer program was then prepared to compute the internal diameter of the flow tubes from the following measured values: (a) test section length in inches; (b) fluid density in grams per cubic centimeter; (c) fluid viscosity as measured by the Cannon-Fenske viscometer in seconds; (d) volume of fluid flow in milliliters; (e) the time of fluid flow in seconds; and (f) pressure in inches of manometric fluid. The basis for the computation is the well known Hagen-Poiseuille law:

$$Q = \pi(P_o - P_1)\, g_c R^4/8\mu L \qquad [2\text{-}3]$$

which appears in computer program #3 in Appendix A in the form of:

$$D = [(128\mu QL)/(\pi\Delta P g_c)]^{\frac{1}{4}} \qquad [2\text{-}4]$$

The results of these calibration runs are summarized in Table 2-3. Computer listings for each of the five flow tubes calibrated in this manner appear in Appendix B.

TABLE 2-3

SUMMARY OF FLOW TUBE DIMENSIONS

Flow Tube Gage Number	Manufacturers Supplied Diameter (Inches)	Calibrated Diameter (Inches)	Test Section Length (Inches)	Entrance Length (Inches)	Exit Length (Inches)
15	0.054	0.05331	5.406	3.99	1.33
13	0.071	0.07158	7.109	5.325	1.78
12	0.085	0.08548	8.500	6.375	2.13
11	0.094	0.09264	9.460	7.05	2.35
10	0.106	0.10590	10.609	7.95	2.65

In addition to providing a means by which the internal diameter of the flow tubes could be accurately measured, the results of these tests indicated that data of reasonable consistency could be obtained in the laminar flow regime using the measurement techniques and instruments employed.

Performance characteristics of the tubes was next tested in the turbulent flow regime corresponding to a range of Reynolds numbers from 10^4 to 10^5. While it would have been desirable to measure these characteristics for each of the five tubes, time limitations permitted detailed examination of only two tubes, number 15 and 13. These calibration experiments were conducted over the same turbulent flow regime using two fluids, military jet fuel (JP4) and tap water. The flow behavior of each of these fluids was thereby independently reproduced.

There were three major objectives to be accomplished during these performance tests:

(a) To determine the interior roughness characteristics of the flow tubes.

(b) To determine the effects, if any, of the pressure ports placed at either end of the test section over the range of Reynolds stresses to which the fluids would be subjected during research experiments.

(c) To observe the performance of the Midwest differential pressure gage as a measuring device under dynamic turbulent flow conditions.

It might be well to recall, in connection with this latter objective, that the characteristics of the Midwest differential pressure gage were originally determined by a calibration technique which produced a *static* pressure differential across the two inlet ports of the gage. Further, there was a clearly defined mechanical hysteresis associated with this gage which appeared when static pressures were being systematically increased and decreased. This observed static behavior raised serious questions of the gage's ability to yield reliable pressure measurements under conditions of turbulent fluid flow which is characterized by violent pressure fluctuations.

It was recognized, of course, that the effects of the pressure ports could only be judged if the interior roughness characteristics failed to conform with well established flow behavior data. The dilemma just described is not uncommon to scientific research: Experimental results cannot be achieved without measurement--yet to measure is to disburb. Further, whether a meaningful discrimination between the first two objectives could be achieved would largely depend upon the performance of the differential pressure gage.

There were, however, some criteria by which the results of these tests could be judged:

(a) The results of the calibration tests on the differential pressure gage suggested a decrease in reliability at the lower pressure ranges. Further, at pressure readings of less than 100 psi, the number of significant digits available was reduced by one.

(b) Any abnormal effects on flow behavior resulting from the pressure ports could be expected to become more pronounced as the flow rates were increased.

(c) The expected minimum friction factor at any particular flow rate would correspond to the friction factor established for "hydraulically smooth" pipes. The expected maximum would not be likely to exceed the friction factor relationship established for drawn tubing.

For the 15 gage flow tube with a 0.053 inch I.D., the maximum expected relative roughness was approximately 0.002. The corresponding value for the 13 gage tube was approximately 0.001.

Using these criteria, the results of the turbulent flow tests as illustrated in Figure 2-5 suggest the following conclusions:

(a) The reliability of pressure measurements taken with the Midwest gage is substantially reduced at differential pressure readings below 75 psi.

(b) The relative roughness of the flow tubes, including any contributing effects of the pressure ports, is between 1/5 and 1/10 the relative roughness associated with drawn tubing.

(c) No abnormal flow behavior can be specifically identified with the pressure ports over the range of shear rates examined during the test.

Hence, it was concluded that the equipment and flow system design were entirely satisfactory for experimental studies on drag reduction. A computer write out of information used to construct Figure 2-5 is contained in Appendix C. Computer program number 4, used to produce this information is contained in Appendix A.

OPERATION OF FLOW SYSTEM

Once a sample had been loaded into the fluid reservoir a choice of the flow tube to be used and the range of the flow regime to be investigated was required in order to determine appropriate measurement equipment. Generally, the Midwest differential pressure gage was employed to measure the pressure drop across the test section at high Reynolds numbers and the flow rate was measured on the Fairbanks Morse Scale by timing a predetermined *weight* of fluid. The mercury manometer was employed to measure the test section pressure differential at the lower Reynolds numbers and the flow of a predetermined *volume* of fluid (up to a maximum of 4000 milliliters) was timed to measure flow rate.

The computer flow model commented upon earlier in this Chapter was used as a guide for these determinations. By referring to Table 2-1, for example, if the flow of pure tap water through the 15 gage tube at a

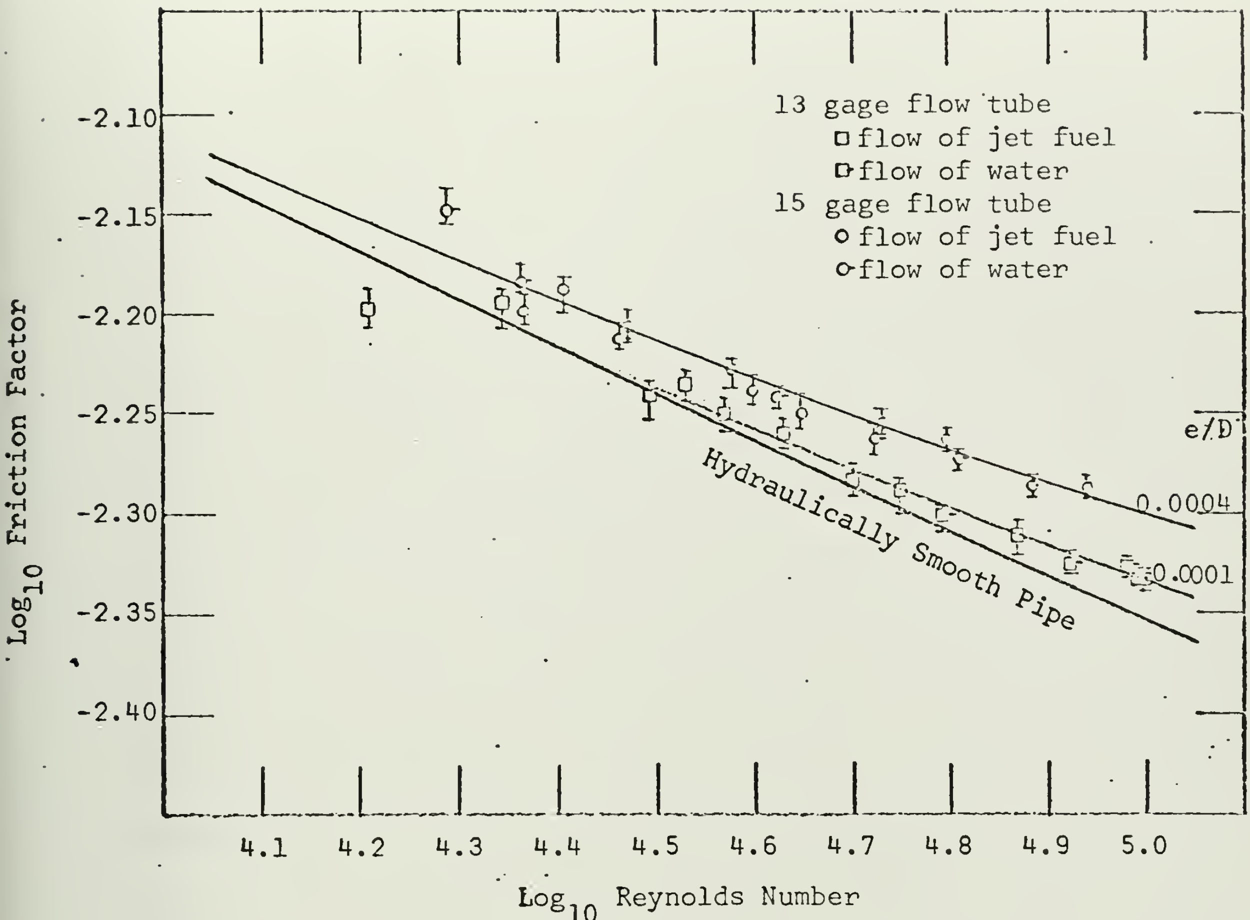

Fig. 2-5. Log-Log Plot of Friction Factor vs. Reynolds Number for Turbulent Flow of Tap Water and Military Jet Fuel in Two Flow Tubes

Reynolds number in the vicinity of 60,000 was to be observed, the pressure regulator from the nitrogen cylinder was set at 800 pounds per square inch and the program indicated that the flow of at least 15 pounds (rounded to the nearest 5 pounds) of the fluid should be timed in order to insure that the timed run would consume at least 100 seconds. Therefore, a series of runs could be preplanned to maximize the efficient use of fluid available for investigation.

Once the flow regime to be investigated had been determined and the appropriate measurement equipment assembled, it was next necessary to purge the tubing leading from the pressure ports of the flow tubes to the pressure gages. This was accomplished by loosening the fittings at the entrance to the gages, plugging the exit end of the flow tube and permitting the fluid to flow through the pressure gage line until a free flow, clear of gas bubbles was observed. Next, a 500 milliliter sample of the fluid was withdrawn from the reservoir from which the basic properties of temperature, density and viscosity were determined. An average measurement of viscosity was obtained on the sample by timing three to five consecutive trial runs in the Cannon-Fenske capillary tube viscometer. Since there was not a means provided to maintain the reservoir fluid at a constant temperature, the fluid properties of the reservoir mixture were measured every 20 to 30 minutes during the course of experimentation. Variations in these properties for a given reservoir load were generally found to be negligible since the maximum time required to empty the cylinder rarely exceeded 45 minutes once experiments were begun. The cylinder used with the Westphal balance and the capillary tube viscometer were each cleaned and dried immediately after use.

Prior to a test run, the weights on the Fairbanks Morse Scale were adjusted to permit two to four pounds of the test fluid to flow before the stop watch was started and measurements were begun. This procedure allowed a sufficient amount of time for the Autoclave 90° valve to be fully opened and permitted the fluid flow pattern to develop and stabilize before measurements were taken. When the arm of the Fairbanks Morse Scale returned to equilibrium, the stop watch was started and the predetermined weights were added to the balance arm. Measurements of

gage pressure at the upstream end of the test section and differential pressure across the test section as well as the weight of fluid to be timed were recorded on a data sheet. When enough fluid entered the collection container on the scale to cause the arm to return to equilibrium, the stop watch was stopped and the flow valve was closed. The temperature of the fluid was then taken and recorded together with the elapsed time for the run.

ANALYSIS OF FLOW DATA

One basis for determining the effectiveness of a polymer would be to relate the friction factor observed for a fluid *with* such an additive to the friction factor observed for a *purely viscous fluid* flowing at the same Reynolds number. The factors affecting the Reynolds number--ie., density, average fluid velocity, tube diameter and fluid viscosity--could all be accurately determined to three or more significant figures. However, the friction factor varies as a direct function of pressure which, when measured with the Midwest differential pressure gage, could be determined to two significant figures at best. Information indicating the scatter in pressure readings expected over the wide range of pressures investigated was available from the calibration runs performed on the gage (see Figure 2-2). This scatter includes an allowance for both the observed mechanical hysteresis as well as the random scatter associated with other limitations of the instrument and observer. This information was used to compute error bounds for each value of friction factor, assuming that the measurements taken with the differential pressure gage represented the least reliable data and would contribute the most significant error.

At the conclusion of a series of runs, data cards were prepared using the information taken during each run. These were used with Computer Program number 4 in Appendix A to analyze the test data.

PREPARATION OF POLYMER SOLUTIONS

The pioneering research undertaken by Fabula and Hoyt (6) at the Naval Ordnance Test Station during the late 1950's and early 1960's

was instrumental in identifying a relatively large number of water soluble polymers capable of inducing drag reduction effects in extremely dilute aqueous solutions. However, an equally extensive program directed toward the identification of additives capable of producing drag reduction effects in dilute, non-polar hydrocarbon solutions has never been undertaken. In fact, prior to Shin's investigation (23), Toms original research (25) appears to be unique, not only because it represents the first written account of drag reduction associated with dilute Newtonian solutions, but also because his experiments involved a non-aqueous solvent. Shaver and Merrill worked with *concentrated* solutions of polyisobutylene in cyclohexane (22). During World War II, an apparent reduction of flow resistance was noted when gasoline was *thickened* with napalm for use in flame throwers (1). However, in contrast to the dilute solutions studied by Toms and Fabula, the final solutions involved in these isolated examples had markedly different fluid characteristics than the original solvents. The fact that polyisobutylene had been shown to be soluble in a pure non-polar hydrocarbon solvent and the fact that it apparently displayed anomalous behavior in concentrated solutions clearly suggested that further study of its behavior in dilute solutions might be productive. Additionally, it seemed appropriate to test the more common water soluble polymers for solubility in jet fuel. For this reason, samples of several polymers known to exhibit viscoelastic properties were initially requested and obtained from various industrial sources. While most of these polymers were known to be soluble in water and sea water, the solubility of each was tested in the jet fuel for possible further examination if time would permit. A summary of the polymer samples and the sources from which they were obtained is contained in Table 2-4.

Several 50 weight part per million solutions in jet fuel were prepared, each containing one of these polymers, and all were observed for several days. Each solution was prepared by carefully weighing a small sample of the polymer (between 34 and 38 milligrams) on a precalibrated precision Metler analytic balance and then adding the volume of jet fuel of carefully measured density that would produce a concentration of 50 weight parts per million. These samples were placed in a one liter

TABLE 2-4

LIST OF POLYMERS OBTAINED AND INDUSTRIAL SOURCE

Company	Product
Archer Daniels Midland Minneapolis, Minn.	Polysacchoride ADM 7079
Enjay Company New York, N.Y.	Polyisobutylene L80, L140 and L200
Union Carbide Corporation New York, N.Y.	Polyox WSR P301, WSR P205, N3000 and N750
Hercules Powder Company Wilmington, Del.	Reten 210, A1 and A5
Stein, Hall & Co., Inc. New York, N.Y.	Jaguar J2S1 Polyhal 27

bottle and were periodically tested for solubility by visual observation. None of the water soluble polymers appeared to be soluble in jet fuel when mixed by natural diffusion techniques at room temperature. Although mixing by diffusion can be a very slow and difficult process for many polymers, it did not appear that more vigorous artificial methods should be employed in view of the well known susceptibility of most polymers to mechanical, thermal and/or chemical degradation. On the other hand, the three samples of polyisobutylene prepared in one liter bottles at concentrations of 50 weight parts per million appeared to be completely dissolved through natural diffusion when left standing at room temperature for approximately 36 hours. The preparation of more concentrated samples was found to be somewhat slower. However, even a 6% weight solution of the highest molecular weight polymer prepared (VISTANEX L-200) was completely dissolved as judged by visual inspection of such factors as homogeneity, clarity, etc., in less than two weeks. The speed with which the mixing occurred appears to be more a function of the total quantity of polymer present in a sample than the weight concentration of the

sample being prepared. That is, a 3% solution prepared in 500 ml size samples dissolved more rapidly than a 3% solution prepared in 1000 ml size batches.

The concentrated polymer solutions were developed to facilitate the preparation of the 50 weight part per million solutions to be loaded into the fluid reservoir for flow experiments. It was found that these solutions once the polymer was fully dissolved, mixed very readily with the pure solvent to form the desired dilute concentration. Thus, by pouring a solution containing 2.267 grams of the polymer into a 20 gallon stainless steel tank and then adding enough jet fuel to bring the total weight to 100 pounds, a 50 wppm sample could be prepared in a very few minutes. In an effort to insure that all of the polymer originally prepared in the one liter bottle was actually included in the 100 pound solution, the bottle was flushed several times with the pure jet fuel which was used to form the final solution.

Since the preparation of large quantities of even dilute concentrations can become a problem, the procedure adopted in this study is certainly recommended. Further, certain physical properties which are impossible to describe quantitatively such as homogeneity, purity, etc. become more difficult to control as the size of the sample increases.

Once the desired dilute solution was formed, it was gently poured into the fluid reservoir at a rate of about 1/2 gallon per minute to minimize any effects of mechanical degradation or depolymerization prior to actual flow through the test section.

CHAPTER III

EXPERIMENTAL RESULTS AND DISCUSSION

All drag reduction experiments were accomplished by observing the flow behavior of solutions containing 50 weight parts per million of the high molecular weight Vistanex L-200 in military jet fuel. The two flow tubes with the smallest diameters were used: number 13 with an 0.0716 inch I. D. and number 15 with an 0.0533 inch I. D. The flow system was primarily operated in the turbulent regime corresponding to a range of Reynolds numbers from approximately 10,000 to 100,000, although a few observations were also made on laminar flow. Values of observed friction factor and Reynolds number were calculated for each run using the same computer program (number 4 in Appendix A) as was used to analyze flow data pertaining to the pure solvents.

The results of the turbulent flow experiments are illustrated in Figure 3-1. (The data is presented in Appendix D.) The friction factor versus Reynolds number relationship found to exist for purely viscous fluids flowing in the turbulent regime, as well as an extension of laminar flow relationships have been included in order to facilitate visual comparison. Error bands have been included on all data calculated from pressure measurements taken with the Midwest D.P.I. gage in order to illustrate the statistical uncertainty observed at the time the gage was calibrated. Flow lines have been drawn which place greatest reliability on the data points calculated from pressure measurements taken with the mercury manometer. These data points do not have error bands.

In examining Figure 3-1 it should be noted that:

(a) At any given Reynolds number, the drag reduction effect appears to be more pronounced as the internal diameter of the flow tube increases.

(b) Over the range of Reynolds stresses covered by these experiments, the drag reduction effect appears to first increase then decrease with increasing Reynolds numbers.

The former occurrence is well known and has been reported since Toms original findings as the "diameter effect." Its importance, however, is often overlooked. It is because of this effect that dynamic

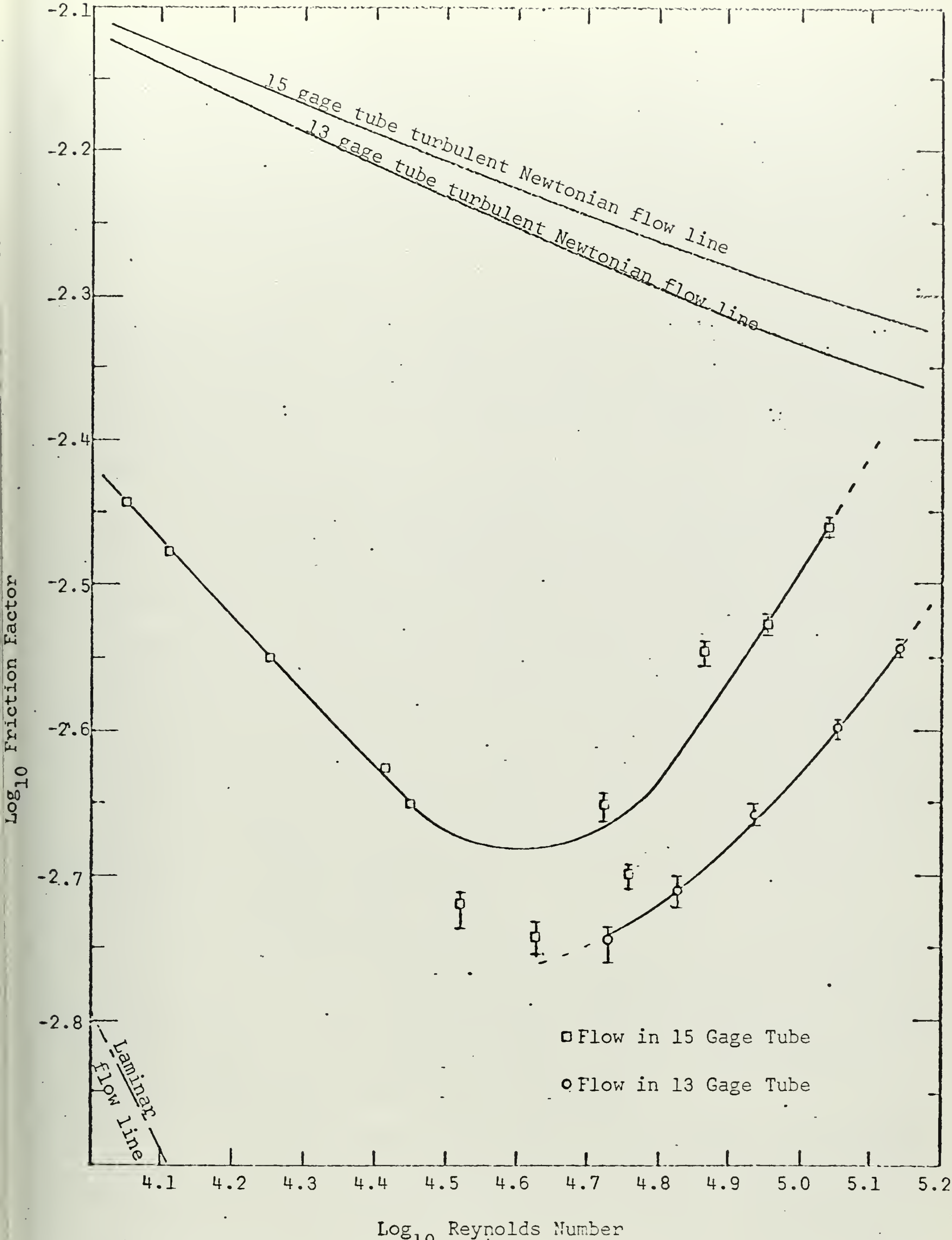

Fig. 3-1. Log-Log Plot of Observed Friction Factor vs. Reynolds Number for the Flow of 50 wppm PIB in Jet Fuel

similarity in the turbulent flow regime is lost. The Reynolds Number Similarity Law for turbulent flow of fluids no longer applies to this unique class of fluids. On the other hand, this anomalous behavior does not occur in the laminar region of fluid flow. A friction factor equal to or slightly higher than the relationship which correlates the Fanning friction factor with the Reynolds number in the laminar regime:

$$f = 16/N_{Re} \qquad [3\text{-}1]$$

was found to apply to this class of fluids. (This data is not illustrated on Figure 3-1 which has been scaled so as to permit graphical amplification of the more important region from $N_{Re}>10^4$. However, the statement can be verified by reference to the complete data included in Appendix D.)

The latter occurrence is somewhat more unique. In general, it has been found that the drag reduction effect becomes more pronounced at increasing flow rates. Many experimenters (6), (18), (19), (23), have observed that there is a critical flow rate beyond which the drag reducing effectiveness of an additive appears to deteriorate. Precisely what determines this critical flow rate has not yet been determined. The critical flow rate appears to be very dependent upon polymer concentration, temperature, the particular polymer used etc., although these observations are not confirmed in this study since only one polymer at one concentration was examined at ambient temperatures. This decrease in friction reducing effectiveness was found to occur at around a Reynolds number of 50,000. It is believed to be indicative of severe mechanical degradation.

At this point in the experimental program, it was believed that greater insight into the drag reduction phenomena could be achieved by a study of this apparent degradation than would be obtained by continuing on the plan originally established for the study. This departure appeared appropriate for a number of reasons:

(a) The recent work of Shin, (23), Hershey, (8), Rodriguez et al. (20) had served to confirm the drag reducing behavior of dilute concentrations of polymers in hydrocarbon solvents. The effects of varying concentrations and flow tube diameters were well documented.

(b) Any practical application of the phenomenon in the field of military logistics as envisioned, must consider the limitations imposed by mechanical degradation.

This is not to suggest that these limitations cannot be advantageously employed. Since the particular additive employed in this study consists of a hydrocarbon polymer of paraffinic structure (26), some form of artificial degradation after fuel transmission has been accomplished might well be preferred as a means of overcoming fuel quality deterioration.

Two methods of artificially imposing mechanical degradation were employed: (a) The first method involved the reuse of a solution which had already been subjected to experimentation. The degradation imposed in this manner might well be representative of the effects to be expected as a result of long distance transmission; (b) The second method involved a modification of the flow system. The modification introduced a means of imposing a very high localized shear point prior to the flow tube. It will be recalled that care was exercised in the original design of the system to eliminate the occurrence of excessive fluid shearing prior to the point at which the fluid entered the flow tube. Even the entrance to the flow tube was tapered to minimize the pressure loss at that location. Indeed, when the 15 gage flow tube was used to observe fluid flowing at a Reynolds number of 100,000 in the tube, the maximum Reynolds number achieved at any other location in the system was approximately 15,000.

The modification for the second method of imposing mechanical degradation was accomplished by inserting a needle valve into the system just upstream of the flow tube. A very high pressure drop could be imposed across this needle valve to produce an extremely high localized Reynolds number. The degradation imposed in this fashion would tend to simulate the mechanical devices often found in a complete closed loop flow system which produce high localized Reynolds stresses such as centrifugal pumps, etc. This system is referred to as the "modified flow system."

The results of these experiments are illustrated in Figure 3-2. The mechanical degradation imposed by both methods employed is clearly apparent. The more severe form would appear to accompany the use of the needle valve in the flow system. The polymer appears to be so degraded that the fluid no longer exhibits any substantial drag reducing characteristics. Even the solution used for the first time through this arrangement (labeled as "first pass through modified flow system") appears to be substantially more degraded than the solution being recycled through the flow system for the second time. These results suggest that flow system design can have a very important effect on the performance of a drag reducing additive. That is, if maximum performance from a drag reducing additive is to be achieved, mechanical devices which produce high localized Reynolds stresses should be avoided. Additives should be injected down stream from such a device.

The mechanical degradation associated with either method appears to have permanently destroyed some of the drag reducing potential of the additive. That is, the friction factors observed for the solution which was passed through the system for the fourth time were consistently higher than those observed during even the third pass.

Further, there would appear to be a striking similarity between the effects on friction drag resulting from the use of a degraded solution and what has been termed "the diameter effect." This suggests that the diameter effect is in fact more properly identified as a degradation effect. That is, the friction reducing capability of a solution is not necessarily decreased by virtue of fluid flow performed in smaller tubes. Rather, the mechanical degradation has been increased. This is not unexpected since the mechanical shear applied to a fluid flowing at a given Reynolds number is substantially increased as tube diameter is decreased. Nonetheless, the friction reducing characteristics of the additive, even in a degraded state, continue to be pronounced when compared to the flow behavior of the pure solvent.

Finally, note the trend of the flow behavior patterns developing at Reynolds numbers between 10,000 and 50,000 as illustrated in Figure 3-2. The friction factor curve produced from experiments using a fresh 50 wppm polyisobutylene solution appears to approach an extension

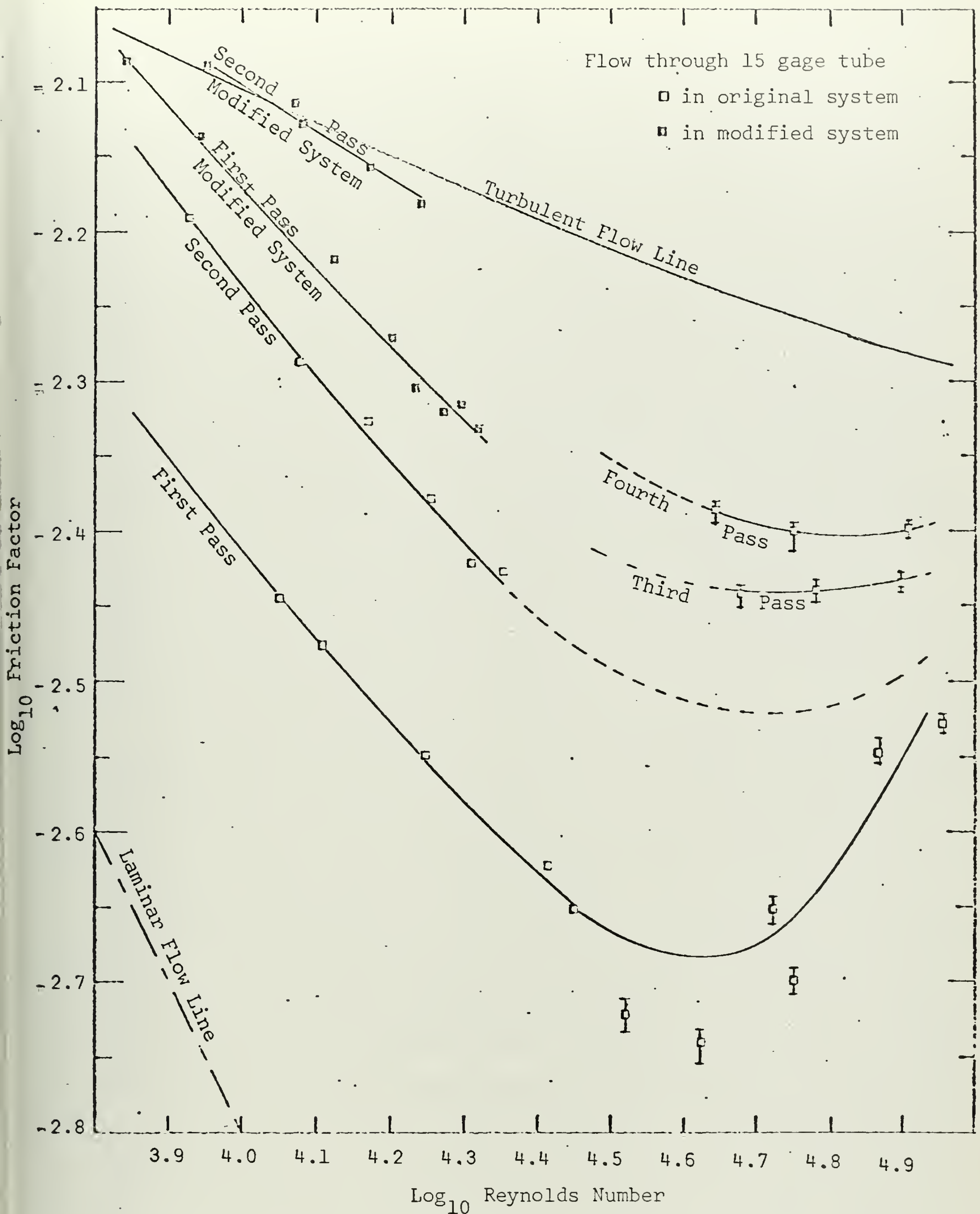

Fig. 3-2. Log-Log Plot of Observed Friction Factor vs. Reynolds Number for the Flow of 50 wppm PIB in Jet Fuel

of the laminar flow curve. On the other hand, the most highly degraded solutions almost coincide with the turbulent friction factor curve.

These characteristics were also observed in a qualitative sense during the flow experiments. During the flow of tap water, pure jet fuel or jet fuel with highly degraded polyisobutylene at well developed turbulent flow rates, a very marked pressure fluctuation was observed which was indicated by a pronounced "flutter" of the Heise gage pointer and manometric fluid. This flutter could be interpreted as variations in the absolute pressure as measured at the wall of the tube corresponding to the turbulent fluctuations known to exist. On the other hand, as the less degraded solutions were used there was a noticeable decrease in the magnitude of the flutter associated with each pressure indicator. When the freshly prepared solution was used, no noticeable flutter could be visually detected. It is recognized that the measuring instruments employed did not possess the sensitivity required to reduce these qualitative observations to quantitative data. Nonetheless, the general pattern just described could be visually detected even if accurate measurements could not be taken and the qualitative significance of these observations should not be ignored.

A practical explanation of this observed behavior might be found in different modes of flow of the solvent and solute. Although the flow of the solvent is known to be turbulent at the Reynolds numbers investigated, little is known concerning the mode of flow of the dissolved solute. It would appear that the combined effect of solvent and solute flowing at a given Reynolds number produces a unique flow regime, the nature of which depends upon the relative (or superimposed) contribution of each. The flow characteristics of the fresher, less degraded solution, least resemble the turbulent characteristics of the pure solvent. The inference is that the pure solute contributes a stabilizing influence more typical of laminar flow, producing a "pseudo-laminar" regime when the effect of the solute is found to dominate. The maximum stabilizing contribution of the solute could be expected to occur at what has been called the "optimum" concentration. At concentrations less than optimum, the turbulent contribution of the solvent begins to dominate. At concentrations greater than optimum the contribution of the solute

continues to dominate. However, because of the thickening action of the solute, the viscous drag could be expected to be somewhat greater than that obtained at an optimum concentration.

Mechanical degradation occurring during a flow experiment can be expected to alter the relative influence of the solute by effectively changing the original concentration. Thus, a highly degraded solution originally containing 50 wppm of solute could be expected to behave like a much weaker undegraded solution. Although this explanation does not attempt to describe the mechanism responsible for drag reduction associated with the solute, it suggests that any attempt to correlate properties of solutions which exhibit drag reduction characteristics must consider the very important influence of mechanical degradation.

Unfortunately, until such a correlation is found, there is no mathematical device through which the performance of a given flow system can be predetermined since the dynamic similarity laws of purely viscous fluids do not appear to apply to this unique class of fluids. However, it can be shown that the rate of fluid flow in a given flow system is proportional to the reciprocal of the square root of the friction factor. That is,

$$Q_{ve} = Q_v \, (f_v/f_{ve})^{\frac{1}{2}} \qquad [3\text{-}2]$$

where: Q represents flow rate;

f represents friction factor;

v refers to a purely viscous fluid; and,

ve refers to a viscoelastic fluid.

Although the precise value to be assigned to f_{ve} is not known, this relationship is useful in assessing the potential benefits to be derived from the drag reduction effect during tactical military replenishment. For example, a 65% reduction in friction factor from a value of 0.00517 to 0.00181 was the highest achieved in this study. The capacity of the flow system to transmit fluids was thereby increased by approximately 69%. Reductions in friction factor of 80% are not uncommon (6, 23). If this reduction could be achieved at a Reynolds number of 10^6, the capacity of the system would be increased by approximately 224%. In other words, the time required to transmit fuel under

these circumstances could be better than halved. Even the solution passed through the system for the fourth time during this study exhibited a 28% decrease in frictional drag at a moderate Reynolds number of 56,000. The flow rate was thereby increased some 17.5%.

Time did not permit the evaluation of quality deterioration introduced by the addition of 50 wppm of polyisobutylene in military jet fuel. It was always recognized that the application of this concept to military logistics could not proceed until this very important phase had been accomplished. However, the benefits of achieving substantial drag reduction with relatively small amounts of additives are believed to be sufficiently attractive to warrant this further effort.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The results of the experimental study on the flow behavior of polyisobutylene dissolved in jet fuel indicate the following conclusions and recommendations for future work.

1. Performance of Flow System The variable pressure, single pass flow system designed and constructed for use in this study was found to be particularly well suited for experimental studies on viscous drag reduction. Flow behavior up to a Reynolds number of 10^5 could be observed using the apparatus as constructed for this study, yet fluid consumption could be minimized by the proper selection of flow tubes. The single pass type test system facilitated the study of shear degradation since the fluid makes only one pass through the test section so that exposure of the fluid to shear stress could be closely controlled. Also, this type of system is quite similar to that used in tactical military refueling operations.

The apparatus was found to perform well in both the laminar and turbulent flow regimes when tested with liquids of known fluid properties. No abnormal flow behavior was identified with the pressure ports of the smaller tubes (numbers 15 and 13) over the range of shear rates examined during the calibration tests. The larger tubes were not used for drag reduction flow tests. However, from an examination of the data taken to determine the internal diameter of the larger tubes, it would appear that the pressure ports might well be influencing the flow behavior in these tubes. Since no drag reduction tests were made using the larger tubes, an analysis of this effect was not performed.

The Midwest differential pressure gage used to measure high test section differential pressures did not provide the precision or range required in this study. Its continued use in future work is not recommended. There are other differential pressure gages available which will provide better precision for a given range of pressure. For future work, several precise differential pressure gages, each selected

to cover a part of the total pressure range anticipated, e.g., 10, 50, and 100% of maximum range, should be used.

It is recommended that a means of controlling the temperature fluctuations of the fluid in the reservoir be provided. These fluctuations, caused by ambient temperature changes in the laboratory, made it necessary to use average values of density and viscosity.

2. Performance of Vistanex L-200 as a Drag Reducing Additive The results of this study indicate that a marked reduction in viscous drag can be achieved by the addition of minute quantities of high molecular weight polyisobutylene in a hydrocarbon solvent. Frictional drag decreases of as much as 65% were noted when turbulent flow experiments were performed with a 50 wppm concentration of Vistanex L-200 dissolved in military jet fuel. The friction reduction was observed to increase with increasing flow tube diameter. Further, friction reduction increased with increasing Reynolds numbers up to a certain "critical" Reynolds number, after which friction reduction decreased with increasing Reynolds numbers. By way of contrast, this anomalous behavior was not observed in the laminar region of fluid flow where frictional drag was slightly higher than that predicted by the Hagen-Poiseuille relationship.

3. Sensitivity of Vistanex L-200 to Mechanical Degradation The solutions of polymer tested were shown to be extremely sensitive to mechanical degradation. Further, repeated testing of a fluid containing a fixed amount of polymer indicated that the drag reducing characteristics of such a solution could be irreversibly destroyed. The degradation was found to occur when the solution was subjected to a region of highly localized shear (a needle valve) as well as to the continuous wall shear in the experimental tubes employed.

Any practical application of the drag reduction phenomenon must consider the limitations imposed by degradation. Therefore, if operational use is contemplated in a full scale flow system, it is recommended that mechanical devices producing high Reynolds stresses be avoided or, alternatively, injection of the additive be accomplished downstream from such a device.

4. <u>Relationship Between Diameter Effect and Degradation</u> Although the results of this study are not conclusive, there appears to be a striking similarity between what has been termed "the diameter effect" and the effects of mechanical degradation. It is therefore recommended that additional work be undertaken to investigate the relationship between the flow tube diameter effect and the mechanical degradation effect of drag reduction.

5. <u>Pseudo-Laminar Flow Characteristics of Fresh Solutions</u> There were strong indications in the experimental work, i.e. the pulsation of the pressure measuring devices, that a suppression of turbulent fluctuations might well be one of the major characteristics associated with the drag reducing influence of an undegraded polymer solution. However, it is recognized that the pressure measuring equipment employed in this study could not permit a quantitative verification of this observation. It is therefore recommended that additional work be undertaken to verify these qualitative observations with pressure sensors with high frequency response, e.g., strain gages.

NOMENCLATURE

Symbol	Definition
d..	derivative of ..
D	flow tube internal diameter
f	Fanning friction factor
g_c	gravitational constant
K	correction to pressure head to account for exit, entrance and kinetic energy losses
L	flow tube test section length
m	parameter in power law model
n	index of non-Newtonian behavior in power law model
N_{Db}	Deborah number
N_{Re}	Reynolds number
P	pressure
Q	volumetric flow rate
R	radius of flow tube
V	average velocity
v	instantaneous velocity
x,y,z	cartesian coordinates

Greek Symbols

Symbol	Definition
μ	Newtonian viscosity
π	3.1415...
ρ	fluid density
τ	shear stress
τ_1	first mode relaxation time of a viscoelastic solution

Subscripts

Symbol	Definition
0,1,2...	evaluated at point 0,1,2...
v	purely viscous fluid
ve	viscoelastic fluid
w	evaluated at the flow tube wall
x,y,z	cartesian coordinates

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APPENDIX A

COMPUTER PROGRAMS USED DURING STUDY

PROGRAM NUMBER 1 COMPUTER MODEL OF NEWTONIAN FLUID FLOW IN SINGLE PASS VARIABLE PRESSURE FLOW SYSTEM

PROGRAM NUMBER 2 COMPUTER PROGRAM TO COMPUTE CALIBRATION CONSTANT OF A CAPILLARY TUBE VISCOMETER

PROGRAM NUMBER 3 COMPUTER PROGRAM TO CALCULATE INTERNAL DIAMETER OF FLOW TUBES

PROGRAM NUMBER 4 COMPUTER PROGRAM TO ANALYZE FLOW DATA

COMPUTER PROGRAM NUMBER 1

Computer Model of Newtonian Fluid Flow in Single Pass Variable Pressure Flow System.

This program was developed to aid in the operation of the single pass variable pressure flow system used in this study. It can also be used to test the effect that variations in flow tube dimensions such as flow tube diameter, test section length, etc., will have on the performance of the flow system. A sample of the output to be expected from this program is found in Table 2-1.

Input data is entered in seven fields each containing 10 columns in an F10.0 format. The Reynolds number (RN) for which performance characteristics are desired is entered in the first field. If the number 200 is entered in this field, the program will compute and write out flow characteristics for fluid flow at various Reynolds numbers in the laminar and turbulent flow regimes up to a maximum Reynolds number of 140,000.

The flow tube diameter (D) in inches is entered in the second field. Fluid viscosity (VISC) in centipoise is entered in the third field. Fluid density (SG) in grams per cubic centimeter is entered in the fourth field. The flow tube exit length (CLD), entrance length (CLU) and test section length (L), all in inches are entered in the fifth, sixth and seventh fields. If any one of these fields is left blank, the program will assume an entrance length of 75 diameters, exit length of 25 diameters, or test section length of 100 diameters for the blank field.

The program will assist in operating the flow system at a given Reynolds number by providing the minimum weight or volume of fluid required to meet the criterion that the flow time for a run last at least 100 seconds and by providing the pressure regulator setting required to achieve the flow regime desired. If the system limitations of available pressure or reservoir capacity are exceeded, the program will automatically signal this condition to the operator. A blank card at the end of the input data will exit the program from the computer. Sample input data are located at the end of the program.

PROGRAM NUMBER 1   COMPUTER MODEL OF NEWTONIAN FLUID FLOW IN
SINGLE PASS VARIABLE PRESSURE FLOW SYSTEM

```
      REAL L,LF,LS
    1 CONTINUE
      WRITE(6,200)
  200 FORMAT(1H1,//////,38X,9HTABLE 2-1,//,
     1                    23X, 34HMODEL OF EXPECTED FLOW PERFORMANCE)
      READ(5,100) RN,D,VISC,SG,CLD,CLU,L
  100 FORMAT(8F10.0)
      IF(RN .LT.  1.0)  CALL EXIT
      IF(L .EQ. 0.) L = 100. * D
      IF(CLU .EQ. 0.0) CLU = 75.0 * D
      IF(CLD .EQ. 0.0) CLD = 25.0 * D
      WRITE(6,201) D
  201 FORMAT(1H0,/,10X,
     1 49HFLOW TUBE DIMENSIONS (INCHES)  FLOW TUBE DIAMETER,F7.4)
      WRITE(6,202) L
  202 FORMAT(41X,19HTEST SECTION LENGTH,F7.3 )
      WRITE(6,203) CLU
  203 FORMAT(41X,15HENTRANCE LENGTH,F7.3)
      WRITE(6,204) CLD
  204 FORMAT(41X,11HEXIT LENGTH,F7.3)
      WRITE(6,205) VISC
  205 FORMAT(1H0, 9X,32HFLUID PROPERTIES--VISCOSITY (CP),F6.3)
      WRITE(6,206) SG
  206 FORMAT(28X,15HDENSITY (GM/CC), F6.3,//)
      WRITE(6,207)
  207 FORMAT(38X,13HEXPECTED     ,13HAMOUNT       ,
     1  9HREQUIRED )
```

```
      WRITE(6,208)
  208 FORMAT(10X,9HREYNOLDS ,9HAVERAGE  , 10HFLOW      ,
     1 13HDIFFERENTIAL ,13HOF FLUID     ,9HRESERVOIR)
      WRITE(6,209)
  209 FORMAT(10X,9HNUMBER   ,9HVELOCITY ,10HRATE      ,
     1  13HPRESSURE     , 13HREQUIRED     , 9HPRESSURE ).
      WRITE(6,210)
  210 FORMAT(38X, 13H(PSI AND/    , 13H(POUNDS AND/ )
      WRITE(6,211)
  211 FORMAT(19X, 9H(FT/SEC) ,10H(GAL/MIN) ,
     1  13H IN. OF HG.) ,13H     LITERS) , 9H  (PSI)  )
      WRITE(6,212)
  212 FORMAT(10X,9H-------- ,9H-------- ,10H--------- ,
     1  13H------------ ,13H------------ ,9H---------,/)
      SIGNAL = RN
      SGMF = 13.546
      SGM = SGMF - SG
      SL = 4.
      SD = 0.125
      TD = 0.3414 / 12.
      TL = 53.5 / 12.
      DS = SD / 12.
      LS = SL / 12.
      RHOCON = (2.54**3)*(12.0**3)/453.56
      VOLCON = (2.54**3)*(12.0**3)
      VISCON = 2.54 * 12.0 /(100. * 453.59)
      RHO = SG * RHOCON
      VISCB = VISC * VISCON
      GC = 32.174
      PI = 3.14159
      CLU = CLU / 12.
```

```
      CLD = CLD / 12.
      DF = D/12.
      LF = L/12.
      CLT = LF + CLU + CLD
      IF(SIGNAL .GT. 201.)  GO TO 5
      K = 2
      I = 22
      M = 2
      N = 100
    4 CONTINUE
      DO 2 J = K,I.M
      IF (J .EQ. 22)  GO TO 3
      RN = J * N
    5 CONTINUF
      V = RN * VISCR / (DF * RHO)
      FRIC = 0.0791 /(RN ** 0.25)
      IF(RN .LT. 2100.) FRIC = 16. / RN
      R = DF / 2.
      AREA = PI * R * R
      QFS = V * AREA
      TESTC = QFS * 100.
      W = QFS * RHO * 100.
      Q = QFS * 60. * 7.481
      QL = Q * 3.7853 * 100. / 60.
      DELP = (RHO * V*V*2.*FRIC *LF)/(    GC *DF *144.)
      PSX = DELP
                           PSH = DELP*407.14/(SGM*14.696)
      PSL = DELP / LF
      PD  = (RHO * V * V /(2. * GC))*(1. +(4. *FRIC * CLD/ DF)) /144.
      PD  = (RHO * V * V /(2. * GC))*(0.1+(4. *FRIC * CLD/ DF)) /144.
      PU = PD + DELP
```

```
      VS = V * DF * DF /(DS*DS)
      RNS = RHO * VS * DS / VISCB
      FRICS= 0.0791 /(RNS** 0.25)
      IF(RNS.LT. 2100.) FRICS= 16. / RNS
      AREAS = PI * DS * DS / 4.
      BETA = AREA / AREAS
      EV = 1.  + 0.45  + 0.9
      EV = 6.
      EV = 4.5
      PSF = PU * 144. + PSL*144. *CLU
      PF = PSF / 144.
      PSE = PSE                            +RHO*V*V*0.45*(1.-BETA)/(2.*GC)
      PSE = PSE + RHO*((V*V)-(VS*VS))/(2. * GC)
      PSF = (RHO * VS* VS/(2. * GC))*(EV +(4. *FRICS* LS / DS)) +PSE
      PSV = PSF / 144.
      VT = V*DF*DF/(TD*TD)
      RNT = RHO*VT*TD/VISCB
      FRICT = 0.0791/(RNT**0.25)
      IF(RNT .LT. 2100.) FRICT = 16./RNT
      AREAT = PI*TD*TD/4.
      BETA = AREAS/AREAT
      PST =PSF+RHO*((VS*VS)-(VT*VT))/(2.*GC)
      PST = PST +RHO*VS*VS*0.45*(1.-BETA)/(2.*GC)
      PST = PST +(RHO*VT*VT/(2.*GC))*(4.*FRICT*TL/TD)
      PSI = PST/144.
      WRITE(6,213)RN,V,Q,PSX,W,PSI
  213 FORMAT(F18.1,F9.1,F10.1,F7.2, F13.1,F16.1)
      WRITE(6,214)PSH,QL
  214 FORMAT(37X,F13.2,F13.3)
      IF(TESTC .GT. 1.5)  GO TO 6
      IF(PSI .GT. 1200.)  GO TO 7
```

```
      IF(SIGNAL .GT. 201.)  GO TO 1
    2 CONTINUE
      GO TO 1
    3 CONTINUE
      K = 20
      I = 140
      M = 20
      N = 1000
      GO TO 4
    6 CONTINUE
      WRITE(6,215)RN
  215 FORMAT(1H0, 9X,33HAT AND ABOVE A REYNOLDS NUMBER OF, F9.1,
     1 20H THE REQUIRED AMOUNT/
     2  10X,39HOF FLUID EXCEEDS THE RESERVOIR CAPACITY,/)
      GO TO 1
    7 CONTINUE
      WRITE(6,216)RN
  216 FORMAT(1H0, 9X,33HAT AND ABOVE A REYNOLDS NUMBER OF, F9.1,
     1  23H THE REQUIRED RESERVOIR,/
     2  10X,37HPRESSURE EXCEEDS THE AVAILABLE SUPPLY,/)
      GO TO 1
      END
```

INPUT DATA FOR PROGRAM NUMBER 1

```
200.      0.0533    1.      1.                        5.406
200.      0.106     1.      1.                        10.609
1000.     0.0533    0.71    1.                        5.406
1000.     0.0533    0.77    1.                        5.406
```

COMPUTER PROGRAM NUMBER 2

Computer Program to Compute a Calibration Constant for a Capillary Tube Viscometer.

This program was developed to compute an average calibration constant for a Cannon-Fenske Capillary Tube Viscometer from data taken during calibration runs. A sample of output to be expected from this program is found in Table 2-2.

Input data is entered in four fields each containing 10 columns in an F10.0 format. The efflux time (TIME) in seconds of the fluid flow in the capillary tube is entered in the first field. The fluid temperature (TEMP) in degrees Celcius is entered in the second field. The fluid density (RHO) in grams per cubic centimeter and fluid viscosity (VIS) in centipoise corresponding to the measured temperature are entered in the third and fourth fields. The program will compute a calibration constant for each calibration run and the arithmetic average of the series of runs. A blank card at the end of the input data deck will exit the program from the computer.

PROGRAM NUMBER 2 COMPUTER PROGRAM TO COMPUTE CALIBRATION CONSTANT OF A CAPILLARY TUBE VISCOMETER

```
      DIMENSION TIME(20),TEMP(20),CON(20),RHO(20),VIS(20),VISK(20)
      WRITE(6,199)
  199 FORMAT(1H1,//////,36X,9HTABLE 2-2,///,17X,
     141HRESULTS ON THE CALIBRATION OF NO. 25/J680,/,25X,
     2  25HCAPILLARY TUBE VISCOMETER,//)
      WRITE(6,204)
  204 FORMAT(1H0,53X,  8HCOMPUTED)
      WRITE(6,205)
  205 FORMAT(10X,7H FLOW  ,8H FLUID  ,9HSTANDARD ,
     1 10HSTANDARD  ,10HKINEMATIC ,11HCALIBRATION)
      WRITE(6,206)
  206 FORMAT(10X,7H TIME  ,8H TEMP.  ,9HDENSITY  ,
     1  10HVISCOSITY ,10HVISCOSITY ,8HCONSTANT)
      WRITE(6,207)
  207 FORMAT(10X,7H(SECS) ,8H(DEG.C) ,9H(GM/CC)  ,
     1  10H   (CP)   ,10H   (CS)   ,9H (CS/SEC))
      WRITE(6,208)
  208  FORMAT(10X,7H------ ,8H------- ,9H-------- ,
     1  10H--------- ,10H--------- ,11H----------,/)
      SUM = 0.
      DO 1 I = 1,20
      READ(5,100) TIME(I),TEMP(I),RHO(I),VIS(I)
  100 FORMAT(8F10.0)
      IF(TIME(I) .LT. 0.1)  GO TO 2
    1 CONTINUE
    2 KT = I - 1
      DO 3 I = 1,KT
```

```
      VIS(I) =1./(2.1482*((TEMP(I)-8.435) +SQRT(8078.4+((TEMP(I)-8.435)
     1  **2.)))-120.)
      VIS(I) = VIS(I) * 100.
      VISK(I) = VIS(I) / RHO(I)
      CON(I) = VISK(I) / TIME(I)
      SUM = SUM + CON(I)
      WRITE(6,200)   TIME(I),TEMP(I),RHO(I),VIS(I),VISK(I),CON(I)
  200 FORMAT(1H0,F15.1,F8.1,F9.4,2F10.4,F12.7)
    3 CONTINUE
      CALCON = SUM/FLOAT(KT)
      WRITE(6,201) CALCON
  201 FORMAT(1H0,/, 10X,
     1               45HCOMPUTED ARITHMETIC AVE. CALIBRATION CONSTANT,
     1 F10.7)
      CALL EXIT
      END
```

9

INPUT DATA FOR PROGRAM NUMBER 2

431.4	21.6	0.997889
431.6	21.6	0.997889
432.8	21.8	0.997844
431.0	22.3	0.997731
426.0	22.6	0.997661
424.0	22.9	0.997591

COMPUTER PROGRAM NUMBER 3

Computer Program to Calculate the Internal Diameter of Flow Tubes.

This program was developed to compute an average internal diameter for the flow tubes to be used with the single pass variable pressure flow system used in this study. A sample of the output to be expected from this program is illustrated in Appendix B.

Each series of data cards containing information taken during flow experiments pertaining to a tube to be calibrated is preceded by a run control card. The run control card contains three data fields each of which contains 10 columns in an F10.0 format. The identifying number (such as the gage number) of the tube is entered in the first field (TUBE). The diameter (SPEC) of the tube in inches as supplied by the manufacturer is entered in the second field. The temperature (TEMP) of the calibration fluid is entered in the third field in degrees Celcius.

The data cards following the run control card contain information required to compute the internal diameter of the flow tube from measurements taken during laminar flow runs. Each data card contains seven data fields each in an F10.0 format. The first 10 column field is left blank. The test section length (L) in inches is entered in the second data field. The elapsed time (T) in seconds required for a predetermined quantity of fluid to flow through the tube is entered in the third data field. The value of fluid density (SG) is entered in the fourth field in grams per cubic centimeters. The value of fluid viscosity (VISC) is entered in the fifth field. This value may be either the efflux time in seconds taken from the calibrated number 25/J680 Cannon-Fenske viscometer, or the value of viscosity in centipoise up to a maximum of 5 cp. The volume (VOL) of fluid examined during the flow experiment expressed in milliliters is entered in the sixth data field. The differential test section pressure (P) which is measured in inches of CCL_4 is entered in the seventh data field. Columns 71-80 are left blank.

A blank card at the end of a series will indicate that the series has been completed and the arithmetic average of the individually

computed diameters will be computed. Two blank cards at the end of a data deck will exit the program from the computer. Sample input data are located at the conclusion of the program list.

PROGRAM NUMBER 3 COMPUTER PROGRAM TO CALCULATE INTERNAL DIAMETER OF FLOW TUBES

```
      REAL L,LF
      DIMENSION TEMP(20)
      I = 1
      KOUNT = 2
      SUM = 0.
    3 CONTINUE
      TOTAL = KOUNT
      SUM = SUM / TOTAL
      WRITE(6,204) SUM
  204 FORMAT(1H0,18X,48HARITHMETIC AVERAGE OF COMPUTED INTERNAL DIAMETER
     1,  F9.5)
      KOUNT = 0
      SUM = 0.
      READ(5,100) TUBE            ,SPEC ,TEMP(I)
      IF(TUBE .LT. 0.1)  CALL EXIT
      WRITE(6,199)
  199 FORMAT(1H1,//////)
      WRITE(6,200) TUBE,SPEC
  200 FORMAT(1H0 25X,35H CALIBRATION OF CAPILLARY TUBE GAGE,F4.0,/25X,
     1  35H MANUFACTURERS SUPPLIED DIAMETER IS,F6.3,/ 29X,
     2  27H PLUS OR MINUS 0.005 INCHES,//)
      WRITE(6,203)
  203 FORMAT(1H0, 9X,9HREYNOLDS ,10HCOMPUTED  ,9HMEASURED ,
     1 10H  FLOW     ,9HPRESSURE ,10HOBSERVED  , 8HCOMPUTED)
      WRITE(6,205)
  205 FORMAT(10X,9HNUMBER   ,10HVISCOSITY ,9HDENSITY  ,
     110H  RATE     ,9HDIFFER.  ,10HFRICTION  ,8HDIAMETER)
```

```
      WRITE(6,206)
  206 FORMAT(19X,10H   (CP)      ,9H(GM/CC)   ,10H(GAL/MIN) ,
     1 9H(IN CCL4),10HFACTOR     ,8H(INCHES))
      WRITE(6,207)
  207 FORMAT(10X,9H-------- ,10H--------- ,9H-------- ,
     1 10H--------- ,9H-------- ,10H--------- ,8H--------,//)
    1 CONTINUE
      READ(5,100) D,L,T,SG,VISC,VOL,P,W
  100 FORMAT     .   (8F10.0)
      IF(T .EQ. 0.0)  GO TO 3
      KOUNT = KOUNT + 1
      SGMF = 1.577
      SGM = SGMF - SG
      GC = 32.174
      G  = 32.174 *(1. -0.00065)
      CALCON = 0.0022283
      PI = 3.14159
      RHOCON = (2.54**3)*(12.0**3)/453.56
      VOLCON = (2.54**3)*(12.0**3)
      VISCON = 2.54 * 12.0 /(100. * 453.59)
      RHO = SG * RHOCON
      VOL = VOL / VOLCON
      Q = VOL / T
      QGAL = Q * 60. * 7.481
                   PSF =P/12.0*SGM*RHOCON * G / GC
      PF = PSF
      LF = L/12.
      DF = D/12.
      IF(VISC .GT. 5.) VISC = VISC * CALCON * SG
      VIS    = VISC * 6.72 E -4
      VIS    = VISC * VISCON
```

```
      IF(D.EQ.0.) DF =(VIS*128.*Q*LF/(PI*PF* GC))** 0.25
      R = DF / 2.
      AREA = PI * R * R
      V = Q/AREA
      RN = RHO * V * DF / VIS
      FOBS = PF * GC * DF/(RHO * 2. * LF * V * V)
      FCAL = 0.0791 /(RN ** 0.25)
      IF(RN .LT. 2100.) FCAL = 16. / RN
      X = 8. * V /(DF)
      Y = DF * PSF /(4. * LF) * GC
      XLOG = ALOG 10 (X)
      YLOG = ALOG 10  (Y)
      ONE = ALOG 10 (X/Y)
      PSI = P
      D = DF * 12.
      SUM = SUM + D
      VISC = VIS / VISCON
      WRITE(6,210)RN,VISC,SG,QGAL,PSI,FOBS,D
  210 FORMAT(1H0,F17.0,F10.4,F9.4,F10.1,F9.1,F10.4,F9.4)
      GO TO 1
      END
```

INPUT DATA FOR PROGRAM NUMBER 3

```
11.     0.094     19.4
        9.460     616.7     0.9974     420.8     500.0     1.5
        9.460     445.0     0.9974     420.8     500.0     2.2
        9.460     303.5     0.9974     420.8     500.0     3.4
        9.460     247.8     0.9974     420.8     500.0     4.3
```

	9.460	204.8	0.9974	420.8	500.0	5.1
	9.460	174.3	0.9974	420.8	500.0	6.1
	9.460	153.7	0.9974	420.8	500.0	7.0
	9.460	144.7	0.9974	420.8	500.0	7.66
15.	0.054	21.6				
	5.406	359.2	0.9975	430.1	30.0	0.85
	5.406	486.6	0.9975	430.1	100.0	2.3
	5.406	184.8	0.9975	430.1	50.0	3.05
	5.406	213.2	0.9975	430.1	90.0	4.70
	5.406	1017.1	0.9975	430.1	500.0	5.53
	5.406	975.21	0.9975	430.1	500.0	5.55
	5.406	508.0	0.9975	430.1	350.0	7.78
	5.406	652.0	0.9975	430.1	500.0	8.6
	5.406	632.4	0.9975	430.1	500.0	8.65
	5.406	486.8	0.9975	430.1	500.0	11.3
	5.406	453.8	0.9975	430.1	500.0	12.15
10.	0.106	18.2				
	10.609	688.7	0.9973	420.8	500.0	0.9
	10.609	383.4	0.9985	420.8	500.	1.75
	10.609	304.0	0.9973	420.8	500.0	2.1
	10.609	264.9	0.9973	420.8	500.0	2.5
	10.609	212.4	0.9985	420.8	500.	2.95
	10.609	194.2	0.9973	420.8	500.0	3.6
	10.609	164.6	0.9973	420.8	500.0	4.4
	10.609	141.0	0.9973	420.8	500.0	5.3
	10.609	127.2	0.9973	420.8	500.0	5.9

13.	0.071	20.9				
	7.109	509.4	0.9973	442.8	100.	0.82
	7.109	272.6	0.9973	442.8	100.	1.54
	7.109	979.7	0.9973	442.8	500.	2.33
	7.109	706.2	0.9973	442.8	500.	3.51
	7.109	504.8	0.9973	442.8	500.	4.48
	7.109	402.8	0.9973	442.8	500.	5.42
	7.109	354.1	0.9973	442.8	500.	6.48
	7.109	283.4	0.9973	442.8	500.	8.22
	7.109	254.4	0.9973	442.8	500.	9.04
	7.109	220.8	0.9973	442.8	500.	10.16
	7.109	199.6	0.9973	442.8	500.	12.08
	7.109	198.3	0.9973	442.8	500.	12.98
	7.109	176.0	0.9973	442.8	500.	14.07
12.	0.085	20.3				
	8.5	1712.0	0.9972	442.3	500.	0.87
	8.5	479.4	0.9972	442.3	500.	2.52
	8.5	302.9	0.9972	442.3	500.	4.25
	8.5	241.8	0.9972	442.3	500.	5.47
	8.5	206.7	0.9972	442.3	500.	6.29
	8.5	183.4	0.9972	442.3	500.	7.32
	8.5	164.0	0.9972	442.3	500.	8.24
	8.5	148.2	0.9972	442.3	500.	9.21
	8.5	140.3	0.9972	442.3	500.	10.13
	8.5	139.9	0.9972	442.3	500.	10.13

COMPUTER PROGRAM NUMBER 4

Computer Program to Analyze Flow Data.

This program was developed to analyze the experimental data taken during flow experiments with the variable pressure single pass flow system. Each series of data cards containing information taken during flow experiments is preceded by two run control cards. The first run control card contains four 10 column input fields in an F10.0 format.

The gage number of the flow tube used during the flow experiments is entered in the first field (TUBE). The density in grams per cubic centimeters of the manometric fluid used to measure differential pressure is entered in the second field (SGMF). The flow diameter (D) and test section length (L) both in inches are entered in the third and fourth fields respectively. The second run control card is in a 65A1 format on which a general description of the experiment is entered.

There are two data cards required to record information pertinent to each flow experiment. The first data card contains eight 10 column fields in an F10.0 format. The first two fields are used to enter the flow tube diameter (D) and test section length (L) both in inches. The third field is used to enter the elapsed time (T) of the flow run in seconds. The value of fluid density (SG) is entered in the fourth field in either CGS units up to 5 grams per cubic centimeter or British Engineering System units for values exceeding 5 pounds per cubic foot. The value of fluid viscosity (VISC) is entered in the fifth field. This value may be either the efflux time in seconds taken from the calibrated number 25/J680 Cannon-Fenske viscometer, the temperature in °C of distilled water if used in the flow experiment between 10-99°C or the value of viscosity in centipoise of the fluid if less than 10 cp. The volume (VO) of fluid examined during the flow experiment expressed in milliliters is entered in the sixth data field if a volumetric measurement is taken. The differential pressure (P) is entered in the seventh data field. This value may be either in inches of manometric fluid when the VO field contains a digit, or pounds per square inch if the VO field is blank. The weight (W) in pounds of fluid examined during the

flow experiment if a weight measurement is taken, is entered in the eighth data field.

The second data card contains three 10 column fields in an F10.0 format. It is used to enter the pressure gage calibration correction (DEV) and maximum (PLUS) and minimum (SUB) expected error bounds associated with the pressure measuring instrument.

A blank card at the end of a series of runs will indicate that the series has been completed. Two blank cards will exit the program from the computer.

A listing of data taken during the flow experiments is located at the end of the program in this Appendix. Examples of output from this program are found in Appendices C and D.

PROGRAM NUMBER 4 COMPUTER PROGRAM TO ANALYZE FLOW DATA

```
      REAL L,LF
      DIMENSION TITLE(65)
      DIMENSION TEMP(20)
      I = 1
    3 CONTINUE
      READ(5,100) TUBE ,SGMF,D,L
      IF(TUBE .LT. 0.1)  CALL EXIT
      READ(5,101) TITLE
  101 FORMAT(65A1)
      WRITE(6,199)
  199 FORMAT(1H1,//////32X,  21HANALYSIS OF FLOW DATA)
      WRITE(6,204) TITLE
  204 FORMAT(1H0,10X,65A1)
      WRITE(6,200) TUBE
  200 FORMAT(32X,   19HIN FLOW TUBE NUMBER,F4.0,//)
      WRITE(6,201) D
  201 FORMAT(1H0,/,14X,
     1 49HFLOW TUBE DIMENSIONS (INCHES)  FLOW TUBE DIAMETER,F7.4)
      WRITE(6,202) L
  202 FORMAT(45X,19HTEST SECTION LENGTH,F7.3,/ )
      WRITE(6,203)
  203 FORMAT(1H0, 9X,9HREYNOLDS ,10HCOMPUTED  ,9HMEASURED ,
     1 10H  FLOW    ,9HPRESSURE ,10HOBSERVED  , 8HCOMPUTED)
      WRITE(6,205)
  205 FORMAT(10X,9HNUMBER   ,10HVISCOSITY ,9HDENSITY  ,
     110H  RATE    ,9HDIFFER.  ,10HFRICTION  ,8HFRICTION)
      WRITE(6,206)
```

```
206 FORMAT(19X,10H   (CP)      ,9H(GM/CC)   ,10H(GAL/MIN) ,
   1 9H (PSI)    ,10HFACTOR     ,8HFACTOR   )
    WRITE(6,207)
207 FORMAT(10X,9H-------- ,10H--------- ,9H-------- ,
   1 10H--------- ,9H-------- ,10H--------- ,8H--------)
  4 CONTINUE
    READ(5,100) D,L,T,SG,VISC,VO ,P,W
100 FORMAT        (8F10.0)
    IF(T .EQ. 0.0)  GO TO 3
    TEMP(I) = VISC
    PINIT = P
    KOUNT = 0
    READ(5,100) DEV,PLUS,SUB
    IF(DEV.EQ.0.0.AND.PLUS.EQ.0.0.AND.SUB.EQ.0.0) KOUNT = 2
  1 CONTINUE
    KOUNT = KOUNT + 1
    IF(KOUNT .EQ. 1)  P =(1. + DEV ) * PINIT
    IF(KOUNT .EQ. 2)  P =(1. + PLUS) * PINIT
    IF(KOUNT .EQ. 3)  P =(1. + SUB ) * PINIT
    IF(KOUNT .EQ. 4 )  GO TO 4
    SGM = SGMF - SG
    GC  = 32.174
    G   = 32.174 *(1. -0.00065)
    CALCON = 0.0022283
    PI = 3.14159
    RHOCON = (2.54**3)*(12.0**3)/453.56
    VOLCON = (2.54**3)*(12.0**3)
    VISCON = 2.54 * 12.0 /(100. * 453.59)
    RHO = SG * RHOCON
    IF(SG .GT. 5.) RHO = SG
    VOL = VO / VOLCON
```

```
      Q = VOL / T
      IF(W .GT. 0.5   ) Q = W/(T*RHO)
      QGAL = Q * 60. * 7.481
      PSF = P * 144.
      IF(VOL .GT. 0.0)
     1                PSF =P/12.0*SGM*RHOCON * G / GC
      PF = PSF
      LF = L/12.
      DF = D/12.
      IF(VISC .GT.99.) VISC = VISC * CALCON * SG
      IF(VISC .GT. 10.0)
     1VISC    =1./(2.1482*((TEMP(I)-8.435) +SQRT(8078.4+((TEMP(I)-8.435)
     1  **2.)))-120.)    * 100.
      VIS    = VISC * VISCON
      IF(VISC .EQ. 0.) VIS = PI*PF*DF**4/(128.*Q*LF) * GC
      IF(D.EQ.0.) DF =(VIS*128.*Q*LF/(PI*PF* GC))** 0.25
      R = DF / 2.
      AREA = PI * R * R
      V = Q/AREA
      RN = RHO * V * DF / VIS
      FOBS = PF * GC * DF/(RHO * 2. * LF * V * V)
      FCAL = 0.0791 /(RN ** 0.25)
      IF(RN .LT. 2100.) FCAL = 16. / RN
      ACAL = ALOG 10 (FCAL)
      AOBS = ALOG 10(FOBS)
      ARN = ALOG 10(RN)
      X = 8. * V /(DF)
      Y = DF * PSF /(4. * LF) * GC
      XLOG = ALOG 10 (X)
      YLOG = ALOG 10  (Y)
      ONE = ALOG 10 (X/Y)
```

```
      PSI = PSF / 144.
      VISC = VIS / VISCON
      IF(W.GT.0.0.AND.KOUNT.EQ.2)    GO TO 2
      IF(W.GT.0.0.AND.KOUNT.EQ.3)    GO TO 5
      WRITE(6,210)RN.VISC.SG.QGAL.PSI,FOBS,FCAL
  210 FORMAT(1H0,F17.0,F10.4.F9.4.F10.2.F9.1,F10.5,F9.5)
      GO TO 1
    2 CONTINUE
      WRITE(6.211)  PSI.FOBS
  211 FORMAT(10X,38HMAX EXPECTED VALUES DUE TO UNCERTAINTY,F8.1,F10.5)
      GO TO 1
    5 CONTINUE
      WRITE(6.212)  PSI.FOBS
  212 FORMAT(10X,38HMIN EXPECTED VALUES DUE TO UNCERTAINTY,F8.1,F10.5)
      GO TO 1
      END
```

INPUT DATA FOR PROGRAM NUMBER 4

```
15.        13.546     0.05333    5.406
         FLOW OF JET  FUEL WITH  DEGRADED PIB (FOURTH PASS)
0.05333    5.406      206.4      0.7685     451.9                 318.       30.
0.005      0.017      -0.005
0.05333    5.406      195.8      0.7685     451.9                 153.       20.
0.02       0.03       0.0
0.05333    5.406      251.       0.7685     451.9                 97.        20.
0.023      0.033

15.        13.546     0.05333    5.406
         FLOW OF JET  FUEL WITH  DEGRADED PIB (THIRD PASS)
0.05333    5.406      141.3      0.7672     447.7                 280.       20.
0.005      0.017      -0.005
0.05333    5.406      184.6      0.7672     447.7                 160.       20.
0.02       0.03       0.0
0.05333    5.406      233.3      0.7672     447.7                 99.        20.
0.023      0.033

15.        13.546     0.05333    5.406
         FLOW OF JET  FUEL WITH  DEGRADED PIB (SECOND PASS)
0.05333    5.406      224.3      0.7669     443.6      2000.      12.1

0.05333    5.406      157.4      0.7669     443.6      2000.      19.8

0.05333    5.406      254.6      0.7669     443.6      4000.      27.5

0.05333    5.406      212.2      0.7669     443.6      4000.      35.0
```

```
0.05333   5.406     188.2     0.7669    443.6     4000.     40.1

0.05333   5.406     169.8     0.7669    443.6     4000.     49.3

15.       13.546    0.05333   5.406
FLOW OF 50WPPM PIB IN JET FUEL(FIRST PASS THRU ORIGINAL SYSTEM)
0.05333   5.406     146.5     0.7652    446.4     4000.     41.95

0.05333   5.406     206.4     0.7652    446.4     4000.     24.95

0.05333   5.406     333.0     0.7652    446.4     4000.     12.2

0.05333   5.406     293.6     0.7652    446.4     4000.     14.64

0.05333   5.406     133.2     0.7652    446.4     4000.     47.4

15.       13.546    0.05333   5.406
FLOW OF 50WPPM PIB IN JET FUEL(FIRST PASS THRU ORIGINAL SYSTEM)
0.05333   5.406     104.4     0.7670    450.8               76.       10.
0.031     0.043
0.05333   5.406     131.0     0.7670    450.8               39.       10.
0.033     0.048
0.05333   5.406     167.4     0.7670    450.8               25.       10.
0.035     0.050
0.05333   5.406     183.4     0.7670    450.8               20.       10.
0.036     0.050
0.05333   5.406     235.6     0.7670    450.8               12.5      10.
0.037     0.050
```

```
13.        0.999      0.07160   7.109
FLOW OF  50WPPM PIB  IN JET FUEL(FIRST PASS THRU ORIGINAL SYSTEM)
0.07160    7.109      104.0     0.7655    455.0                375.       35.
-0.002     0.005      -0.013
0.07160    7.109      108.0     0.7655    455.0                221.       30.
0.012      0.020
0.07160    7.109      115.8     0.7655    462.4                116.       25.
0.023      0.033
0.07160    7.109      119.4     0.7655    462.4                61.        20.
0.031      0.045
0.07160    7.109      110.4     0.7655    462.4                37.        15.
0.038      0.048

15.        0.999      0.05333   5.406
FLOW OF  50WPPM PIB  IN JET FUEL(FIRST PASS THRU ORIGINAL SYSTEM)
0.05333    5.406      106.2     0.7633    433.2                473.       20.
-0.004     0.002      -0.015
0.05333    5.406      94.1      0.7633    433.2                285.       15.
0.005      0.017      -0.005
0.05333    5.406      118.5     0.7633    433.2                172.       15.
0.02       0.03       0.0
0.05333    5.406      101.8     0.7633    433.2                72.        10.
0.028      0.04       0.0
0.05333    5.406      324.3     0.7633    433.2     100.       8.15
0.0        0.0        0.0
0.05333    5.406      357.5     0.7653    433.2     500.       34.0
0.0        0.0        0.0
```

```
15.         13.546    0.05333   5.406
FLOW OF JP4 WITH DEGRADED PIB (SECOND PASS THRU MODIFIED SYSTEM)
0.05333    5.406      221.4     0.7669    443.6     4000.     50.3

0.05333    5.406      258.0     0.7669    443.6     4000.     39.5

0.05333    5.406      316.2     0.7669    443.6     4000.     28.3

0.05333    5.406      426.6     0.7669    443.6     4000.     17.1

0.05333    5.406      317.0     0.7669    443.6     4000.     29.0


15.         13.546    0.05333   5.406
FLOW OF 50WPPM PIB IN JET FUEL(FIRST PASS THRU MODIFIED SYSTEM)
0.05333    5.406      204.2     0.7654    447.0     4000.     43.0

0.05333    5.406      196.1     0.7654    447.0     4000.     47.6

0.05333    5.406      188.6     0.7654    447.0     4000.     50.1

0.05333    5.406      233.6     0.7654    447.0     4000.     37.3

0.05333    5.406      278.0     0.7654    447.0     4000.     29.7


15.         13.546    0.05333   5.406
FLOW OF 50WPPM PIB IN JET FUEL(FIRST PASS THRU MODIFIED SYSTEM)
0.05333    5.406      222.6     0.7642    445.0     4000.     37.7

0.05333    5.406      330.4     0.7642    445.0     4000.     21.8
```

```
0.05333    5.406     216.7      0.7642    445.0     2000.     14.7

0.05333    5.406     272.6      0.7642    445.0     2000.     10.4

0.05333    5.406     361.8      0.7642    445.0     2000.     6.1

0.05333    5.406     116.8      0.7642    445.0     500.      4.05

0.05333    5.406     135.6      0.7642    445.0     500.      2.87

0.05333    5.406     168.1      0.7642    445.0     500.      1.95

0.05333    5.406     178.3      0.7642    445.0     500.      1.64

0.05333    5.406     207.0      0.7642    445.0     500.      1.15

0.05333    5.406     338.4      0.7642    445.0     500.      0.63

0.05333    5.406     541.9      0.7642    445.0     500.      0.39


15.        0.999     0.05333    5.406
13.        13.546    0.07160    7.109
FLOW OF PURE JP4 TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS
0.0716     7.109     134.       0.7610    420.1               268.      30.
0.005      0.017     -0.005
0.0716     7.109     119.2      0.7610    420.1               156.      20.
0.02       0.03      0.0
0.0716     7.109     97.3       0.7610    420.1               75.       11.
0.028      0.04      0.0
0.07160    7.109     111.6      0.7644    448.9               105.      15.
0.025      0.034     0.000
```

0.07160	7.109	146.0	0.7644	448.9	65.	15.
0.031	0.045	0.000				
0.07160	7.109	133.0	0.7644	448.9	36.	10.
0.035	0.046	0.004				
0.07160	7.109	112.2	0.7644	448.9	50.	10.
0.031	0.045	0.000				
0.07160	7.109	95.0	0.7644	448.9	25.	6.
0.038	0.050	0.008				

15.   13.546   0.05333   5.406

FLOW OF PURE JP4 TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS

0.05333	5.406	147.2	0.7613	430.0	100.	10.
0.025	0.038	0.001				
0.05333	5.406	119.7	0.7613	430.0	174.	11.
0.016	0.028	0.001				
0.05333	5.406	139.0	0.7613	430.0	313.	17.5
0.005	0.015	-0.007				
0.05333	5.406	101.2	0.7613	430.0	439.	15.
-0.004	0.002	-0.015				
0.05333	5.406	137.7	0.7644	436.4	245.	15.
0.01	0.022	-0.004				
0.05333	5.406	161.2	0.7644	436.4	181.	15.
0.018	0.028	0.001				

15.   13.546   0.05333   5.406

FLOW OF PURE JP4 TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS

0.05333	5.406	129.6	0.7644	436.4	125.	10.
0.025	0.033	0.005				
0.05333	5.406	152.	0.7644	436.4	95.	10.
0.028	0.036	0.008				
0.05333	5.406	116.8	0.7644	436.4	61.	6.
0.032	0.042	0.010				

```
0.05333    5.406      183.4      0.7657     465.5                  67.        10.
0.031      0.045      0.0
0.05333    5.406      210.6      0.7657     465.5                  54.        10.
0.031      0.045      0.0
0.05333    5.406      242.7      0.7657     465.5                  40.        10.
0.035      0.046      0.004
0.05333    5.406      333.0      0.7657     465.5                  21.        10.
0.038      0.050      0.008

10.        13.546     0.10593    10.609
FLOW OF PURE JP4 TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS
0.10593    10.609     98.0       0.7633     439.5                  126.0      31.
0.023      0.035      0.000
0.10593    10.609     120.9      0.7633     439.5                  85.        31.
0.027      0.039      0.000
0.10593    10.609     99.2       0.7638     449.3                  62.        20.
0.031      0.045      0.000
0.10593    10.609     122.0      0.7638     449.3                  37.        20.
0.035      0.046      0.004
0.10593    10.609     164.7      0.7638     449.3                  20.        20.
0.038      0.050      0.008

15.        1.577      0.05333    5.406
FLOW OF TAP WATER TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS
0.05333    5.406      100.25     0.9975     21.2                   362.       15.
0.00001    0.007      -0.016
0.05333    5.406      122.9      0.99874    17.4                   415.       20.
-0.003     0.004      -0.016
0.05333    5.406      149.0      0.99874    17.2                   287.       20.
0.005      0.011      -0.005
0.05333    5.406      94.2       0.99874    17.2                   187.       10.
0.015      0.023      0.001
```

```
0.05333    5.406     134.2     0.99874   17.0                 98.     10.
0.025      0.035     0.001
0.05333    5.406     102.      0.99874   17.0                 65.     6.
0.03       0.038     0.01
0.05333    5.406     101.2     0.99874   17.1                 50.     5.
0.03       0.038     0.01

13.        1.577     0.07160   7.109
FLOW OF TAP WATER TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS
0.07160    7.109     92.4      0.99868   17.6                 437.    30.
-0.005     0.001     -0.014
0.07160    7.109     89.2      0.99868   17.5                 330.    25.
0.002      0.008     -0.009
0.07160    7.109     85.6      0.99868   17.5                 256.    21.
0.008      0.015     -0.001
0.0716     7.109     57.2      0.99804   20.8                 160.    11.
0.017      0.026     0.004

10.        1.577     0.10593   10.609
FLOW OF TAP WATER TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS
0.10593    10.609    83.2      0.9975    19.3                 122.    30.
0.024      0.031     0.002
0.10593    10.609    74.6      0.9975    19.6                 74.     20.
0.027      0.037     0.002
0.10593    10.609    69.6      0.9975    19.5                 51.     15.
0.03       0.038     0.001
0.10593    10.609    87.4      0.9975    17.7                 312.    50.
0.002      0.008     -0.009
0.10593    10.609    71.8      0.9975    17.9                 168.    30.
0.015      0.023     0.001
```

15.	1.577	0.05333	5.406			
	LAMINAR	FLOW TEST	USING PURE	TAP WATER		
0.05333	5.406	184.8	0.9975	430.1	50.0	3.05
0.05333	5.406	213.2	0.9975	430.1	90.0	4.70
0.05333	5.406	508.0	0.9975	430.1	350.0	7.78
0.05333	5.406	1017.1	0.9975	430.1	500.0	5.53
0.05333	5.406	975.21	0.9975	430.1	500.0	5.55
0.05333	5.406	632.4	0.9975	430.1	500.0	8.65
0.05333	5.406	652.0	0.9975	430.1	500.0	8.6
0.05333	5.406	453.8	0.9975	430.1	500.0	12.15
0.05333	5.406	486.8	0.9975	430.1	500.0	11.3

13.	1.577	0.07160	7.109			
	LAMINAR FLOW TEST USING PURE TAP WATER					
0.07160	7.109	979.7	0.9973	442.8	500.	2.33
0.07160	7.109	706.2	0.9973	442.8	500.	3.51
0.07160	7.109	504.8	0.9973	442.8	500.	4.48
0.07160	7.109	402.8	0.9973	442.8	500.	5.42
0.07160	7.109	354.1	0.9973	442.8	500.	6.48
0.07160	7.109	283.4	0.9973	442.8	500.	8.22
0.07160	7.109	254.4	0.9973	442.8	500.	9.04
0.07160	7.109	220.8	0.9973	442.8	500.	10.16
0.07160	7.109	199.6	0.9973	442.8	500.	12.08
0.07160	7.109	188.3	0.9973	442.8	500.	12.98
0.07160	7.109	176.0	0.9973	442.8	500.	14.07

APPENDIX B

COMPUTER WRITE OUT

RESULTS OF THE CALCULATIONS TO DETERMINE

FLOW TUBE INTERNAL DIAMETER

CALIBRATION OF CAPILLARY TUBE GAGE 15.
MANUFACTURERS SUPPLIED DIAMETER IS 0.054
PLUS OR MINUS 0.005 INCHES

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (IN CCL4)	OBSERVED FRICTION FACTOR	COMPUTED DIAMETER (INCHES)
80.	0.9560	0.9975	0.0	0.9	0.1992	0.0544
202.	0.9560	0.9975	0.0	2.3	0.0791	0.0531
267.	0.9560	0.9975	0.0	3.1	0.0599	0.0530
415.	0.9560	0.9975	0.0	4.7	0.0385	0.0532
485.	0.9560	0.9975	0.0	5.5	0.0330	0.0530
501.	0.9560	0.9975	0.0	5.6	0.0320	0.0536
680.	0.9560	0.9975	0.0	7.8	0.0235	0.0530
756.	0.9560	0.9975	0.0	8.6	0.0212	0.0531
774.	0.9560	0.9975	0.0	8.6	0.0207	0.0534
1007.	0.9560	0.9975	0.0	11.3	0.0159	0.0533
1081.	0.9560	0.9975	0.0	12.1	0.0148	0.0533

ARITHMETIC AVERAGE OF COMPUTED INTERNAL DIAMETER 0.05331

CALIBRATION OF CAPILLARY TUBE GAGE 13.
MANUFACTURERS SUPPLIED DIAMETER IS 0.071
PLUS OR MINUS 0.005 INCHES

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (IN CCL4)	OBSERVED FRICTION FACTOR	COMPUTED DIAMETER (INCHES)
136.	0.9840	0.9973	0.0	0.8	0.1176	0.0733
255.	0.9840	0.9973	0.0	1.5	0.0628	0.0732
362.	0.9840	0.9973	0.0	2.3	0.0442	0.0717
512.	0.9840	0.9973	0.0	3.5	0.0312	0.0702
700.	0.9840	0.9973	0.0	4.5	0.0228	0.0718
870.	0.9840	0.9973	0.0	5.4	0.0184	0.0725
1002.	0.9840	0.9973	0.0	6.5	0.0160	0.0716
1257.	0.9840	0.9973	0.0	8.2	0.0127	0.0713
1396.	0.9840	0.9973	0.0	9.0	0.0115	0.0715
1598.	0.9840	0.9973	0.0	10.2	0.0100	0.0720
1800.	0.9840	0.9973	0.0	12.1	0.0089	0.0707
1915.	0.9840	0.9973	0.0	13.0	0.0084	0.0705
2055.	0.9840	0.9973	0.0	14.1	0.0078	0.0702

ARITHMETIC AVERAGE OF COMPUTED INTERNAL DIAMETER 0.07158

CALIBRATION OF CAPILLARY TUBE GAGE 12.
MANUFACTURERS SUPPLIED DIAMETER IS 0.085
PLUS OR MINUS 0.005 INCHES

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (IN CCL4)	OBSERVED FRICTION FACTOR	COMPUTED DIAMETER (INCHES)
178.	0.9828	0.9972	0.0	0.9	0.0898	0.0834
604.	0.9828	0.9972	0.0	2.5	0.0265	0.0878
971.	0.9828	0.9972	0.0	4.3	0.0165	0.0865
1225.	0.9828	0.9972	0.0	5.5	0.0131	0.0859
1427.	0.9828	0.9972	0.0	6.3	0.0112	0.0863
1621.	0.9828	0.9972	0.0	7.3	0.0099	0.0856
1815.	0.9828	0.9972	0.0	8.2	0.0088	0.0854
2014.	0.9828	0.9972	0.1	9.2	0.0079	0.0852
2149.	0.9828	0.9972	0.1	10.1	0.0074	0.0844
2154.	0.9828	0.9972	0.1	10.1	0.0074	0.0844

ARITHMETIC AVERAGE OF COMPUTED INTERNAL DIAMETER 0.08548

CALIBRATION OF CAPILLARY TUBE GAGE 11.
MANUFACTURERS SUPPLIED DIAMETER IS 0.094
PLUS OR MINUS 0.005 INCHES

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (IN CCL4)	OBSERVED FRICTION FACTOR	COMPUTED DIAMETER (INCHES)
455.	0.9352	0.9974	0.0	1.5	0.0352	0.0953
639.	0.9352	0.9974	0.0	2.2	0.0250	0.0939
950.	0.9352	0.9974	0.0	3.4	0.0168	0.0927
1173.	0.9352	0.9974	0.0	4.3	0.0136	0.0920
1412.	0.9352	0.9974	0.0	5.1	0.0113	0.0924
1667.	0.9352	0.9974	0.0	6.1	0.0096	0.0920
1896.	0.9352	0.9974	0.1	7.0	0.0084	0.0917
2029.	0.9352	0.9974	0.1	7.7	0.0079	0.0911

ARITHMETIC AVERAGE OF COMPUTED INTERNAL DIAMETER 0.09264

CALIBRATION OF CAPILLARY TUBE GAGE 10.
MANUFACTURERS SUPPLIED DIAMETER IS 0.106
PLUS OR MINUS 0.005 INCHES

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (IN CCL4)	OBSERVED FRICTION FACTOR	COMPUTED DIAMETER (INCHES)
358.	0.9351	0.9973	0.0	0.9	0.0447	0.1084
656.	0.9363	0.9985	0.0	1.8	0.0244	0.1063
817.	0.9351	0.9973	0.0	2.1	0.0196	0.1076
947.	0.9351	0.9973	0.0	2.5	0.0169	0.1066
1164.	0.9363	0.9985	0.0	2.9	0.0138	0.1082
1309.	0.9351	0.9973	0.0	3.6	0.0122	0.1051
1558.	0.9351	0.9973	0.0	4.4	0.0103	0.1042
1833.	0.9351	0.9973	0.1	5.3	0.0087	0.1034
2034.	0.9351	0.9973	0.1	5.9	0.0079	0.1033

ARITHMETIC AVERAGE OF COMPUTED INTERNAL DIAMETER 0.10590

APPENDIX C

COMPUTER WRITE OUT

RESULTS OF FLOW DATA TAKEN

TO DETERMINE INTERNAL CHARACTERISTICS OF FLOW TUBES

ANALYSIS OF FLOW DATA

FLOW OF TAP WATER TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
65350.	0.9762	0.9975	1.08	362.0	0.00554	0.00495
MAX EXPECTED VALUES DUE TO UNCERTAINTY				364.5	0.00558	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				356.2	0.00545	
64731.	1.0718	0.9987	1.17	413.8	0.00536	0.00496
MAX EXPECTED VALUES DUE TO UNCERTAINTY				416.7	0.00539	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				408.4	0.00529	
53122.	1.0773	0.9987	0.97	288.4	0.00549	0.00521
MAX EXPECTED VALUES DUE TO UNCERTAINTY				290.2	0.00552	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				285.6	0.00543	
42013.	1.0773	0.9987	0.76	189.8	0.00577	0.00552
MAX EXPECTED VALUES DUE TO UNCERTAINTY				191.3	0.00582	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				187.2	0.00570	
29341.	1.0828	0.9987	0.54	100.4	0.00620	0.00604
MAX EXPECTED VALUES DUE TO UNCERTAINTY				101.4	0.00626	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				98.1	0.00606	
23162.	1.0828	0.9987	0.42	66.9	0.00663	0.00641
MAX EXPECTED VALUES DUE TO UNCERTAINTY				67.5	0.00669	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				65.6	0.00651	
19504.	1.0800	0.9987	0.36	51.5	0.00723	0.00669
MAX EXPECTED VALUES DUE TO UNCERTAINTY				51.9	0.00729	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				50.5	0.00709	

ANALYSIS OF FLOW DATA

FLOW OF PURE JP4 TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
44257.	0.7433	0.7644	0.73	128.1	0.00565	0.00545
MAX EXPECTED VALUES DUE TO UNCERTAINTY				129.1	0.00569	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				125.6	0.00554	
37735.	0.7433	0.7644	0.62	97.7	0.00592	0.00568
MAX EXPECTED VALUES DUE TO UNCERTAINTY				98.4	0.00597	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				95.8	0.00581	
29464.	0.7433	0.7644	0.48	63.0	0.00626	0.00604
MAX EXPECTED VALUES DUE TO UNCERTAINTY				63.6	0.00632	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				61.6	0.00613	
29270.	0.7942	0.7657	0.51	69.1	0.00611	0.00605
MAX EXPECTED VALUES DUE TO UNCERTAINTY				70.0	0.00619	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				67.0	0.00592	
25489.	0.7942	0.7657	0.45	55.7	0.00649	0.00626
MAX EXPECTED VALUES DUE TO UNCERTAINTY				56.4	0.00658	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				54.0	0.00630	
22118.	0.7942	0.7657	0.39	41.4	0.00641	0.00649
MAX EXPECTED VALUES DUE TO UNCERTAINTY				41.8	0.00648	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				40.2	0.00622	
16120.	0.7942	0.7657	0.28	21.8	0.00635	0.00702
MAX EXPECTED VALUES DUE TO UNCERTAINTY				22.0	0.00643	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				21.2	0.00617	

ANALYSIS OF FLOW DATA

FLOW OF PURE JP4 TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
39707.	0.7295	0.7613	0.64	102.5	0.00580	0.00560
MAX EXPECTED VALUES DUE TO UNCERTAINTY				103.8	0.00588	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				100.1	0.00567	
53712.	0.7295	0.7613	0.87	176.8	0.00547	0.00520
MAX EXPECTED VALUES DUE TO UNCERTAINTY				178.9	0.00554	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				174.2	0.00539	
73586.	0.7295	0.7613	1.19	314.6	0.00519	0.00480
MAX EXPECTED VALUES DUE TO UNCERTAINTY				317.7	0.00524	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				310.8	0.00512	
86633.	0.7295	0.7613	1.40	437.2	0.00520	0.00461
MAX EXPECTED VALUES DUE TO UNCERTAINTY				439.9	0.00523	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				432.4	0.00514	
62481.	0.7433	0.7644	1.02	247.4	0.00547	0.00500
MAX EXPECTED VALUES DUE TO UNCERTAINTY				250.4	0.00554	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				244.0	0.00540	
53372.	0.7433	0.7644	0.88	184.3	0.00558	0.00520
MAX EXPECTED VALUES DUE TO UNCERTAINTY				185.1	0.00564	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				181.2	0.00549	

ANALYSIS OF FLOW DATA

FLOW OF TAP WATER TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS IN FLOW TUBE NUMBER 13.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0716
TEST SECTION LENGTH 7.109

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
96680.	1.0664	0.9987	2.34	434.8	0.00469	0.00449
MAX EXPECTED VALUES DUE TO UNCERTAINTY				437.4	0.00472	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				430.9	0.00465	
83247.	1.0691	0.9987	2.02	330.7	0.00479	0.00466
MAX EXPECTED VALUES DUE TO UNCERTAINTY				332.6	0.00482	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				327.0	0.00474	
72868.	1.0691	0.9987	1.77	258.0	0.00488	0.00481
MAX EXPECTED VALUES DUE TO UNCERTAINTY				259.8	0.00491	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				255.7	0.00483	
61962.	0.9856	0.9980	1.39	162.7	0.00500	0.00501
MAX EXPECTED VALUES DUE TO UNCERTAINTY				164.2	0.00505	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				160.6	0.00494	

ANALYSIS OF FLOW DATA

FLOW OF PURE JP4 TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS IN FLOW TUBE NUMBER 13.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0716
TEST SECTION LENGTH 7.109

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
99800.	0.7124	0.7610	2.12	269.3	0.00466	0.00445
MAX EXPECTED VALUES DUE TO UNCERTAINTY				272.6	0.00471	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				266.7	0.00461	
74795.	0.7124	0.7610	1.59	159.1	0.00490	0.00478
MAX EXPECTED VALUES DUE TO UNCERTAINTY				160.7	0.00495	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				156.0	0.00480	
50396.	0.7124	0.7610	1.07	77.1	0.00523	0.00528
MAX EXPECTED VALUES DUE TO UNCERTAINTY				78.0	0.00529	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				75.0	0.00509	
55823.	0.7646	0.7644	1.26	107.6	0.00519	0.00515
MAX EXPECTED VALUES DUE TO UNCERTAINTY				108.6	0.00523	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				105.0	0.00506	
42670.	0.7646	0.7644	0.97	67.0	0.00553	0.00550
MAX EXPECTED VALUES DUE TO UNCERTAINTY				67.9	0.00560	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				65.0	0.00536	
31227.	0.7646	0.7644	0.71	37.3	0.00574	0.00595
MAX EXPECTED VALUES DUE TO UNCERTAINTY				37.7	0.00580	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				36.1	0.00557	
37016.	0.7646	0.7644	0.84	51.5	0.00565	0.00570
MAX EXPECTED VALUES DUE TO UNCERTAINTY				52.2	0.00573	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				50.0	0.00548	
26231.	0.7646	0.7644	0.59	25.9	0.00566	0.00622
MAX EXPECTED VALUES DUE TO UNCERTAINTY				26.2	0.00573	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				25.2	0.00550	

ANALYSIS OF FLOW DATA

FLOW OF TAP WATER TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS IN FLOW TUBE NUMBER 10.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.1059
TEST SECTION LENGTH 10.609

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
75713.	1.0222	0.9975	2.60	124.9	0.00518	0.00477
MAX EXPECTED VALUES DUE TO UNCERTAINTY				125.8	0.00522	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				122.2	0.00507	
56710.	1.0147	0.9975	1.93	76.0	0.00570	0.00513
MAX EXPECTED VALUES DUE TO UNCERTAINTY				76.7	0.00576	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				74.1	0.00557	
45477.	1.0172	0.9975	1.55	52.5	0.00610	0.00542
MAX EXPECTED VALUES DUE TO UNCERTAINTY				52.9	0.00615	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				51.1	0.00593	
115435.	1.0638	0.9975	4.12	312.6	0.00515	0.00429
MAX EXPECTED VALUES DUE TO UNCERTAINTY				314.5	0.00518	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				309.2	0.00510	
84734.	1.0584	0.9975	3.01	170.5	0.00527	0.00464
MAX EXPECTED VALUES DUE TO UNCERTAINTY				171.9	0.00531	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				168.2	0.00520	

ANALYSIS OF FLOW DATA

FLOW OF PURE JP4 TO DETERMINE INTERIOR ROUGHNESS CHARACTERISTICS IN FLOW TUBE NUMBER 10.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.1059
TEST SECTION LENGTH 10.609

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
90830.	0.7475	0.7633	2.98	128.9	0.00532	0.00456
MAX EXPECTED VALUES DUE TO UNCERTAINTY				130.4	0.00538	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				126.0	0.00520	
73626.	0.7475	0.7633	2.42	87.3	0.00548	0.00480
MAX EXPECTED VALUES DUE TO UNCERTAINTY				88.3	0.00555	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				85.0	0.00534	
56591.	0.7647	0.7638	1.90	63.9	0.00650	0.00513
MAX EXPECTED VALUES DUE TO UNCERTAINTY				64.8	0.00659	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				62.0	0.00630	
46015.	0.7647	0.7638	1.54	38.3	0.00589	0.00540
MAX EXPECTED VALUES DUE TO UNCERTAINTY				38.7	0.00595	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				37.1	0.00571	
34085.	0.7647	0.7638	1.14	20.8	0.00582	0.00582
MAX EXPECTED VALUES DUE TO UNCERTAINTY				21.0	0.00588	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				20.2	0.00565	

ANALYSIS OF FLOW DATA

LAMINAR FLOW TEST USING PURE TAP WATER
IN FLOW TUBE NUMBER 13.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0716
TEST SECTION LENGTH 7.109

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
362.	0.9840	0.9973	0.01	0.0	0.04398	0.04418
502.	0.9840	0.9973	0.01	0.1	0.03443	0.03185
703.	0.9840	0.9973	0.02	0.1	0.02245	0.02276
881.	0.9840	0.9973	0.02	0.1	0.01730	0.01816
1002.	0.9840	0.9973	0.02	0.1	0.01598	0.01597
1252.	0.9840	0.9973	0.03	0.2	0.01298	0.01278
1395.	0.9840	0.9973	0.03	0.2	0.01151	0.01147
1607.	0.9840	0.9973	0.04	0.2	0.00974	0.00996
1778.	0.9840	0.9973	0.04	0.3	0.00947	0.00900
1884.	0.9840	0.9973	0.04	0.3	0.00905	0.00849
2016.	0.9840	0.9973	0.05	0.3	0.00857	0.00794

ANALYSIS OF FLOW DATA

LAMINAR FLOW TEST USING PURE TAP WATER
IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
265.	0.9560	0.9975	0.00	0.1	0.06172	0.06029
414.	0.9560	0.9975	0.01	0.1	0.03907	0.03864
676.	0.9560	0.9975	0.01	0.2	0.02428	0.02368
482.	0.9560	0.9975	0.01	0.1	0.03390	0.03318
503.	0.9560	0.9975	0.01	0.1	0.03128	0.03182
775.	0.9560	0.9975	0.01	0.2	0.02050	0.02063
752.	0.9560	0.9975	0.01	0.2	0.02166	0.02127
1081.	0.9560	0.9975	0.02	0.3	0.01483	0.01481
1007.	0.9560	0.9975	0.02	0.2	0.01587	0.01588

APPENDIX D

COMPUTER WRITE OUT

RESULTS OF FLOW DATA TAKEN

DURING DRAG REDUCTION EXPERIMENTS

(FLOW OF 50 WPPM PIB IN MILITARY JET FUEL)

ANALYSIS OF FLOW DATA

FLOW OF JET FUEL WITH DEGRADED PIB (FOURTH PASS)
IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
80079.	0.7739	0.7685	1.36	319.6	0.00399	0.00470
MAX EXPECTED VALUES DUE TO UNCERTAINTY				323.4	0.00404	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				316.4	0.00395	
56276.	0.7739	0.7685	0.96	155.1	0.00395	0.00514
MAX EXPECTED VALUES DUE TO UNCERTAINTY				157.6	0.00398	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				153.0	0.00387	
43900.	0.7739	0.7685	0.75	99.2	0.00412	0.00546
MAX EXPECTED VALUES DUE TO UNCERTAINTY				100.2	0.00416	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				97.0	0.00403	

ANALYSIS OF FLOW DATA

FLOW OF JET FUEL WITH DEGRADED PIB (THIRD PASS)
IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
78847.	0.7654	0.7672	1.33	281.4	0.00370	0.00472
MAX EXPECTED VALUES DUE TO UNCERTAINTY				284.8	0.00374	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				278.6	0.00366	
60353.	0.7654	0.7672	1.02	163.2	0.00366	0.00505
MAX EXPECTED VALUES DUE TO UNCERTAINTY				164.8	0.00370	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				160.0	0.00359	
47755.	0.7654	0.7672	0.80	101.3	0.00363	0.00535
MAX EXPECTED VALUES DUE TO UNCERTAINTY				102.3	0.00367	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				99.0	0.00355	

ANALYSIS OF FLOW DATA

FLOW OF JET FUEL WITH DEGRADED PIB (SECOND PASS)
IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
8479.	0.7581	0.7669	0.14	5.6	0.00647	0.00824
12084.	0.7581	0.7669	0.20	9.1	0.00521	0.00754
14941.	0.7581	0.7669	0.25	12.7	0.00473	0.00715
17926.	0.7581	0.7669	0.30	16.1	0.00419	0.00684
20212.	0.7581	0.7669	0.34	18.5	0.00377	0.00663
22402.	0.7581	0.7669	0.37	22.7	0.00377	0.00647

ANALYSIS OF FLOW DATA

FLOW OF 50WPPM PIB IN JET FUEL(FIRST PASS THRU ORIGINAL SYSTEM)
IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
25802.	0.7612	0.7652	0.43	19.4	0.00240	0.00624
18314.	0.7612	0.7652	0.31	11.5	0.00283	0.00680
11351.	0.7612	0.7652	0.19	5.6	0.00360	0.00766
12875.	0.7612	0.7652	0.22	6.8	0.00336	0.00743
28379.	0.7612	0.7652	0.48	21.9	0.00224	0.00609

ANALYSIS OF FLOW DATA

FLOW OF 50WPPM PIB IN JET FUEL(FIRST PASS THRU ORIGINAL SYSTEM)
IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP).	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
53005.	0.7705	0.7670	0.90	78.4	0.00225	0.00521
MAX EXPECTED VALUES DUE TO UNCERTAINTY				79.3	0.00227	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				76.0	0.00218	
42242.	0.7705	0.7670	0.72	40.3	0.00182	0.00552
MAX EXPECTED VALUES DUE TO UNCERTAINTY				40.9	0.00185	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				39.0	0.00176	
33057.	0.7705	0.7670	0.56	25.9	0.00191	0.00587
MAX EXPECTED VALUES DUE TO UNCERTAINTY				26.2	0.00194	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				25.0	0.00184	
30173.	0.7705	0.7670	0.51	20.7	0.00184	0.00600
MAX EXPECTED VALUES DUE TO UNCERTAINTY				21.0	0.00186	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				20.0	0.00177	
23483.	0.7705	0.7670	0.40	13.0	0.00189	0.00639
MAX EXPECTED VALUES DUE TO UNCERTAINTY				13.1	0.00192	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				12.5	0.00183	

ANALYSIS OF FLOW DATA

FLOW OF 50WPPM PIB IN JET FUEL(FIRST PASS THRU ORIGINAL SYSTEM)
IN FLOW TUBE NUMBER 13.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0716
TEST SECTION LENGTH 7.109

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP).	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
137699.	0.7761	0.7655	3.16	374.2	0.00288	0.00411
MAX EXPECTED VALUES DUE TO UNCERTAINTY				376.9	0.00290	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				370.1	0.00285	
113657.	0.7761	0.7655	2.61	223.7	0.00253	0.00431
MAX EXPECTED VALUES DUE TO UNCERTAINTY				225.4	0.00255	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				221.0	0.00250	
86920.	0.7887	0.7655	2.03	118.7	0.00222	0.00461
MAX EXPECTED VALUES DUE TO UNCERTAINTY				119.8	0.00224	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				116.0	0.00217	
67440.	0.7887	0.7655	1.57	62.9	0.00195	0.00491
MAX EXPECTED VALUES DUE TO UNCERTAINTY				63.7	0.00198	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				61.0	0.00190	
54703.	0.7887	0.7655	1.28	38.4	0.00181	0.00517
MAX EXPECTED VALUES DUE TO UNCERTAINTY				38.8	0.00183	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				37.0	0.00175	

ANALYSIS OF FLOW DATA

FLOW OF 50WPPM PIB IN JET FUEL(FIRST PASS THRU ORIGINAL SYSTEM)
IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
108972.	0.7368	0.7633	1.77	471.1	0.00348	0.00435
MAX EXPECTED VALUES DUE TO UNCERTAINTY				473.9	0.00350	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				465.9	0.00344	
92239.	0.7368	0.7633	1.50	286.4	0.00295	0.00454
MAX EXPECTED VALUES DUE TO UNCERTAINTY				287.8	0.00299	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				283.6	0.00292	
73246.	0.7368	0.7633	1.19	175.4	0.00287	0.00481
MAX EXPECTED VALUES DUE TO UNCERTAINTY				177.2	0.00290	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				172.0	0.00281	
56841.	0.7368	0.7633	0.93	74.0	0.00201	0.00512
MAX EXPECTED VALUES DUE TO UNCERTAINTY				74.9	0.00203	
MIN EXPECTED VALUES DUE TO UNCERTAINTY				72.0	0.00196	
300.	0.7368	0.7633	0.00	0.1	0.06749	0.05328
1362.	0.7387	0.7653	0.02	0.3	0.01353	0.01175

ANALYSIS OF FLOW DATA

FLOW OF JP4 WITH DEGRADED PIB (SECOND PASS THRU MODIFIED SYSTEM) IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
17181.	0.7581	0.7669	0.29	23.2	0.00655	0.00691
14744.	0.7581	0.7669	0.25	18.2	0.00698	0.00718
12030.	0.7581	0.7669	0.20	13.1	0.00751	0.00755
8917.	0.7581	0.7669	0.15	7.9	0.00826	0.00814
12000.	0.7581	0.7669	0.20	13.4	0.00774	0.00756

ANALYSIS OF FLOW DATA

FLOW OF 50WPPM PIB IN JET FUEL(FIRST PASS THRU MODIFIED SYSTEM)
IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
18487.	0.7624	0.7654	0.31	19.8	0.00477	0.00678
19250.	0.7624	0.7654	0.32	22.0	0.00487	0.00672
20016.	0.7624	0.7654	0.34	23.1	0.00474	0.00665
16160.	0.7624	0.7654	0.27	17.2	0.00542	0.00702
13579.	0.7624	0.7654	0.23	13.7	0.00611	0.00733

ANALYSIS OF FLOW DATA

FLOW OF 50WPPM PIB IN JET FUEL(FIRST PASS THRU MODIFIED SYSTEM) IN FLOW TUBE NUMBER 15.

FLOW TUBE DIMENSIONS (INCHES) FLOW TUBE DIAMETER 0.0533
TEST SECTION LENGTH 5.406

REYNOLDS NUMBER	COMPUTED VISCOSITY (CP)	MEASURED DENSITY (GM/CC)	FLOW RATE (GAL/MIN)	PRESSURE DIFFER. (PSI)	OBSERVED FRICTION FACTOR	COMPUTED FRICTION FACTOR
17035.	0.7578	0.7642	0.28	17.4	0.00498	0.00692
11477.	0.7578	0.7642	0.19	10.1	0.00634	0.00764
8749.	0.7578	0.7642	0.15	6.8	0.00736	0.00818
6955.	0.7578	0.7642	0.12	4.8	0.00824	0.00866
5240.	0.7578	0.7642	0.09	2.8	0.00851	0.00930
4058.	0.7578	0.7642	0.07	1.9	0.00943	0.00991
3496.	0.7578	0.7642	0.06	1.3	0.00900	0.01029
2820.	0.7578	0.7642	0.05	0.9	0.00940	0.01085
2658.	0.7578	0.7642	0.04	0.8	0.00889	0.01102
2290.	0.7578	0.7642	0.04	0.5	0.00841	0.01143
1401.	0.7578	0.7642	0.02	0.3	0.01231	0.01142
875.	0.7578	0.7642	0.01	0.2	0.01954	0.01829